

PROCEEDINGS

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CONFERENCE ON RESEARCH FOR THE DEVELOPMENT OF GEOTHERMAL ENERGY RESOURCES

September 23 - 25, 1974
Pasadena, California

Organized by
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California Institute of Technology

December 31, 1974

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16. Abstract <p>The Conference on Research for the Development of Geothermal Energy Resources was held in Pasadena, California, on September 23, 24, and 25, 1974, under the sponsorship of the National Science Foundation - Research Applied to National Needs (NSF-RANN) program. The conference was held in recognition of the pressing need for expanded energy supply systems. Geothermal energy is one possible candidate source that has received increasing attention in recent years owing to its continued success in electric power and thermal energy production. New applications and technologies for geothermal energy are being actively pursued throughout the world in light of the energy crisis and the recent sharp increases in the cost of conventional fuels. More recently, the Federal government has initiated a move to undertake a significant research and development effort directed towards enhancing the utility of geothermal resources.</p> <p>The purpose of the conference was to acquaint potential user groups with the Federal and NSF geothermal programs and the mechanism by which the users and other interested members of the public sector can participate on those programs. Spokesmen from industry presented papers to describe the critical needs of industry and the non-government sponsored research activity currently underway to address many of these needs.</p>			
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The National Science Foundation wishes to acknowledge the good services of those who contributed to the success of the Conference on Research for Development of Geothermal Energy Resources. Our compliments go to the authors of thirty technical and programmatic papers and to six panelists, who together provided the intellectual content of the conference and whose papers are documented in the proceedings.

The Jet Propulsion Laboratory (JPL) and the California Institute of Technology (Caltech) deserve rich congratulations for planning and implementing the myriad of details essential to a successful public gathering and for hosting some 600 conference attendees with warmth and efficiency. Specifically, congratulations are due to Mr. Yukio Nakamura, Conference Chairman, and his staff at JPL and Caltech: Miss Joyce Yamaguchi, Mrs. Nancy Hopkins, and Mrs. Phyllis Jelinek. We also appreciate the guidance and support given to the conference by Dr. Eugene Shoemaker, Conference Co-Chairman, and Dr. Barclay Kamb, Chairman, Geological and Planetary Sciences Division, Caltech.

A special thanks goes to Dr. Carel Otte for his banquet address preceding the final day of the conference. His observations on the historical development and economics of the nation's current energy shortage were not only sobering but served well to underscore with a sense of urgency the tasks of research for development of this inherently domestic energy resource — geothermal energy.

Finally, we at NSF thank the many in attendance at the conference from industry, the universities, scientific laboratories, and sister agencies of government. Through the earnest and sustained efforts of these people and the institutions they represent, geothermal energy development will be accelerated to help secure for the country reliable, economical energy supplies.

Ritchie B. Coryell
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PREFACE

The Conference on Research for the Development of Geothermal Energy Resources was held in Pasadena, California, on September 23, 24, and 25, 1974, under the sponsorship of the National Science Foundation - Research Applied to National Needs (NSF-RANN) program. The conference was held in recognition of the pressing need for expanded energy supply systems. Geothermal energy is one possible candidate source that has received increasing attention in recent years owing to its continued success in electric power and thermal energy production. New applications and technologies for geothermal energy are being actively pursued throughout the world in light of the energy crisis and the recent sharp increases in the cost of conventional fuels. More recently, the Federal government has initiated a move to undertake a significant research and development effort directed towards enhancing the utility of geothermal resources.

The purpose of this conference was to acquaint potential user groups with the Federal and NSF geothermal programs and the mechanism by which the users and other interested members of the public sector can participate on those programs. Additionally, spokesmen from industry were invited to present papers to describe the critical needs of industry and the non-government sponsored research activity currently underway to address many of these needs.

These proceedings were prepared and published by the Jet Propulsion Laboratory under NSF Grant No. AG-545. The contents of the papers and the opinions expressed are those of the participants and do not necessarily reflect the views of the Jet Propulsion Laboratory, the California Institute of Technology, or the National Science Foundation.

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INTRODUCTION

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INTRODUCTION

CONFERENCE CHAIRMAN: Yukio Nakamura

INTRODUCTION AND CONFERENCE OVERVIEW – R. B. Coryell

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INTRODUCTION AND CONFERENCE OVERVIEW

Ritchie B. Coryell
Geothermal Program Manager
National Science Foundation
Washington, D.C.

This geothermal conference is called to present, for the first time, the Federal Geothermal Energy Research Program to the industry and to the public. Papers have been prepared by many who are currently active in this program to inform you on (1) key organizational and procedural characteristics of the program, and (2) exciting scientific and technological developments currently underway in the program.

The potential of our country's geothermal energy resources to help meet our mounting energy needs warrants our best national efforts to develop these resources as expeditiously and wisely as possible. This conference is designed to give you as full a picture as possible in two and one half days of what is presently being done in the Federal Geothermal Program and what is likely to be done in the future.

However, because we recognize that resource development is a private sector responsibility and that private industry already has much knowledge of and experience with geothermal technology, we want in this conference to hear from you. We want some feedback on the needs in the industry, the opportunities from private perspectives to make geothermal energy real in our country, and your ideas for new directions in the federal program.

Thus, you will hear papers grouped in six half-day sessions. Session I will be programmatic papers delivered by spokesmen of the federal agencies with major budgetary responsibilities in geothermal energy. Sessions II - V will present technical papers on current work by researchers with federal funding support. Finally, Session VI will be a panel discussion with industry spokesmen to offer the private sector perspectives and feedback we need. There will also be an opportunity in each of the sessions for questions from the floor and discussion of matters raised by the speakers.

When JPL first expressed an interest in putting on a geothermal energy conference, early in the year, we felt it would be an opportune way to present the NSF program and give our grantees a chance to show off what they had done. However, it soon became apparent that there is a more important need to acquaint the industry and the public with the whole federal program in geothermal energy. As lead federal agency for the program, NSF has a responsibility in this, and thus the occasion of this conference is seized to unfold as

fully as we can the Federal Geothermal Energy Research and Technology Program.

This program was put together with the active assistance of the conference program committee, whose membership I would like now to introduce to you:

Yukio Nakamura, Chairman (Jet Propulsion Laboratory)

Eugene M. Shoemaker, Co-Chairman (California Institute of Technology)

David N. Anderson (California Division of Oil and Gas and Geothermal Resources Council)

Ben Bayliss (Magma Energy, Inc.)

Wilfred Elders (University of California, Riverside)

Martin Fulcher (U.S. Bureau of Reclamation)

Ben Holt (The Ben Holt Company)

Pat Muffler (U.S. Geological Survey)

John Shupe (University of Hawaii)

Donald Stewart (Battelle-Northwest)

Louis B. Werner (U.S. Atomic Energy Commission)

SESSION I

OPENING SESSION

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SESSION CHAIRMAN: R. B. Coryell

THE NATIONAL GEOTHERMAL ENERGY RESEARCH
PROGRAM - R. J. Green

THE NSF/RANN FY 1975 PROGRAM FOR GEOTHERMAL
RESOURCES AND TECHNOLOGY - P. Kruger

GEOTHERMAL RESEARCH AND DEVELOPMENT PROGRAM
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ENERGY RESEARCH AND DEVELOPMENT - G. P. Eaton and
D. W. Klick (abstract only)

THE NATIONAL GEOTHERMAL ENERGY
RESEARCH PROGRAM

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The continuous demand for energy and the concern for shortages of conventional energy resources have spurred the nation to consider alternate energy resources, such as geothermal. Although significant growth in the one natural steam field located in the United States has occurred, a major effort is now needed if geothermal energy, in its several forms, is to contribute to the nation's energy supplies. From the early informal efforts of an Interagency Panel for Geothermal Energy Research, a 5-year Federal program has evolved whose objective is the rapid development of a commercial industry for the utilization of geothermal resources for electric power production and other products. The Federal program seeks to evaluate the realistic potential of geothermal energy, to support the necessary research and technology needed to demonstrate the economic and environmental feasibility of the several types of geothermal resources, and to address the legal and institutional problems concerned in the stimulation and regulation of this new industry.

Geothermal energy is becoming a small but viable contributor to U.S. energy supplies. However, its development must be greatly accelerated if it is to contribute to meeting urgent domestic energy needs on a significant scale.

Geothermal waters have been used since ancient time; they have been used for municipal heating in Iceland since the 1930's and are being used to a small extent in the United States. Electric power production from geothermal energy began in 1904 at the Larderello Field in Italy. Today, somewhat more than 1000 MWe are being generated in the world. By comparison, single fossil-fueled or nuclear generators are now installed in units which often exceed the world's total geothermal capacity.

The U.S. geothermal resource base has been compared favorably with present oil and gas reserves. It is believed that the most readily exploitable geothermal resources are located in the western third of the U.S. Their development could have considerable impact on meeting the power requirements of the nation. For instance, it has been estimated that the Imperial Valley in California is capable of sustaining a generating capacity of as much as 100,000 MWe for 50 years.

Only one geothermal resource, dry steam, is presently being used to produce power in the United States, generating more than 400 MWe at the Geysers in California. There are no other known sources of dry steam in the U.S. except those in Yellowstone National Park. However, several other resource types show promise. They are: hot brines, moderate temperature/low salinity fluids, geopressured reservoirs, hot rock formations, and magmatic deposits.

It appears to me that the major problems inhibiting the growth of geothermal energy in the U.S. are: (1) a lack of confidence on the part of the energy utilization industry in geothermal reservoirs as reliable, long-term supplies of energy; (2) institutional, legal, and environmental problems associated with the development of such reservoirs; and (3) unsolved technical problems and economic uncertainties concerning the utilization of geothermal energy in an environmentally acceptable manner.

The goal of the National Program is to provide the knowledge and technology base to solve these problems.

There are several strategies which could be adopted to foster the growth of geothermal energy utilization in the United States. One is to give the government exclusive control over all phases from resource exploration to commercial power generation. This is clearly unacceptable. Another strategy would be no government involvement at all. This is undesirable in view of the high-risk nature of exploration, the need for advanced technology for the more marginal types of resources, and the urgency of our energy supply situation.

The strategy that makes most sense — and the one we have adopted — is based upon a short-term government involvement with the geothermal industry. The private sector is expected to assume an increasing role, and a greater share of the risk, as the National Research Program begins to pay off.

Thus, the National Geothermal Energy Research Program places major emphasis on a strong and continuous working relationship with the geothermal energy industry. This will ensure a rapid transfer of research results and, hopefully, achieve the acceleration of the development of U.S. geothermal resources.

The primary goal of the National Geothermal Energy Research Program is to stimulate the private sector to augment the commercial production of electric power by 20,000 to 30,000 MWe by 1985. This would save the equivalent of 1,000,000 barrels of oil per day. The corresponding production goals for 1990 and the year 2000 are 100,000 and 200,000 MWe, respectively. In addition, fossil fuels will also be conserved through the use of geothermal fluids for nonelectric purposes — space heating, process heat, production of minerals, and desalination.

Specifically, the National Program is directed to:

- (1) Provide the necessary technological advances to improve the economics of geothermal power production.
- (2) Expand the knowledge of recoverable resources of geothermal energy.

- (3) Provide carefully researched policy options to assist in resolving environmental, legal, and institutional problems.

The National Program is divided into four discrete areas:

- (1) Resource exploration and assessment.
- (2) Environmental, legal, and institutional problems.
- (3) Resource utilization projects.
- (4) Advanced research and technology.

Resource exploration and assessment is directed at appraising regionally and nationally all types of geothermal resources and identifying promising target areas for industry exploration and development.

The objectives are to improve geophysical, geochemical, geological, hydrological, and other techniques for locating and evaluating geothermal resources; to develop better methods for predicting the productivity and longevity of geothermal reservoirs; and to assess the nature and power potential of the deeper unexplored sectors of high-temperature geothermal convection systems.

Environmental, legal, and institutional research will investigate methods for improved waste disposal and evaluate surface and subsurface effects of geothermal production. The research will seek to improve the capability to predict environmental impacts, expedite preparation of environmental impact statements, and ensure compliance with standards and criteria. Social, legal, and economic problems will be identified. Policy alternatives will be developed to provide a socio-economic framework conducive to commercial utilization of geothermal resources.

Resource utilization projects will provide operational, technological, and economic data to establish the practicality of commercial electric and nonelectric uses of geothermal energy. Small scale, experimental research facilities or pilot plants of 1 to 10 MWe in size will be the vehicle to gain the data and experience. The pilot plants will provide data for use in determining the operating characteristics of commercial scale plants and the potential lifetime of different classes of reservoirs. The facilities will provide the capability to test and evaluate new components developed by industry and universities. The program is directed at involving engineers, analysts, technicians, and managers from industry so that they can gain "hands-on" geothermal power plant experience. Development of a cadre of trained geothermal engineers and technicians is another goal of this program.

The advanced research and technology efforts are directed at a variety of problems. Some examples are: the development of effective, efficient drilling methods for operation in the high-temperature geothermal regime; the development of predictive methods and control techniques for the extraction and reinjection of geothermal fluids; the development of rock fracturing techniques; the improvement of equipment and technology to extract fluids from reservoirs; the development of new energy conversion technology; and, lastly, the development of new and improved methods for controlling emissions and wastes from geothermal reservoirs.

The National Geothermal Energy Research Program involves the activities of many agencies: the National Science Foundation, the Atomic Energy Commission, the U.S. Geological Survey, the Bureau of Reclamation, the Bureau of Mines, the Environmental Protection Agency, the Council of Environmental Quality, the Federal Power Commission, and the Bureau of Land Management.

The National Science Foundation serves as the lead Federal agency for the formulation and execution of the National Program. An Interagency Panel for Geothermal Energy Research has been established to provide the foundation with a mechanism for coordinating the geothermal programs of the Federal agencies.

The panel, including representatives from the agencies listed below, serves as the focal point to ensure that all Federal efforts are properly integrated.

The Interagency Panel for Geothermal Energy Research includes representatives from:

- Atomic Energy Commission
- Bureau of Mines
- Bureau of Reclamation
- Council on Environmental Quality
- Department of Defense
- Department of Interior
- Environmental Protection Agency
- Federal Energy Agency
- Federal Power Commission
- National Science Foundation
- U.S. Geological Survey

Office of Management and Budget (observer)

Private sector involvement in the National Geothermal Energy Research Program will be accomplished through use of the following management approaches:

Industrial organizations and consortia thereof will be awarded contracts to design, construct, manage, and operate experimental research facilities. In these instances, a major benefit will be the flow of information and results directly to the private sector.

Secondly, national laboratories will award contracts to industrial firms for the completion of specific tasks associated with particular projects. Technical and management control will remain with the national laboratory.

I would like to note that in both cases cost sharing arrangements with industrial partners will be sought for the dual purposes of: (1) promoting early participation by the private sector on a "partnership" basis, and (2) reducing the government's cost.

In addition, through both solicited and unsolicited proposals, awards will be made to universities, industry and nonprofit organizations to conduct research in the areas discussed previously. This will ensure that the program will have a steady flow of innovative research ideas and project opportunities.

It is vital to the Federal geothermal effort that close ties with industry be established and maintained. One vehicle for accomplishing this will be the Geothermal Industry Liaison Group. The group will give advice regarding the scope, direction, and planned implementation of geothermal research conducted by Federal agencies.

It will be the means by which the Interagency Panel for Geothermal Energy Research can inform industry of the status of ongoing programs. It will provide the Interagency Panel with industry perspectives on the problems related to geothermal exploitation. Lastly, it will provide the Interagency Panel with recommendations relating to industry participation in the program.

The group will include representatives from:

- (1) Electric utilities.
- (2) Resource extraction organizations.
- (3) Engineering services.
- (4) Agriculture and mining.
- (5) Financial institutions.
- (6) State and local governments.

In addition to scientists and engineers, the group will include representatives concerned with rate base and marketing matters to ensure that the widest range of private sector attitudes and perspectives are available to the government.

The research budget for the national programs in fiscal year 1975 is shown below. We believe it provides for addressing, in a timely way, the problems which inhibit geothermal developments.

1975 Program Budget
(millions of dollars)

	<u>NSF</u>	<u>AEC</u>	<u>DOI</u>	<u>Total</u>
Resource exploration and assessment	3.0	--	8.2	11.2
Environmental, legal, and institutional	2.3	--	1.1	3.4
Resource utilization projects	9.5	9.6	--	19.1
Advanced research and technology	<u>7.5</u>	<u>2.1</u>	<u>1.9</u>	<u>11.5</u>
Total	22.3	11.7	11.2	45.2

The 5-year projected budget for the program is \$314 million dollars. The degree that this is reduced will depend upon private sector cost sharing in the program.

In closing, I would like to say that in developing the National Program Plan we attempted to identify the problems to be overcome to bring geothermal energy to the market place on a large scale. We have attempted to design a program to help in solving these problems. It is based on optimism. We are optimistic that the resource base does in fact exist. We are optimistic that technology can be brought to bear to extract and utilize the resource. And we are optimistic that there are no insurmountable legal, environmental, and institutional problems.

Any program worth its salt is dynamic — it is subject to improvement and upgrading. To ensure that this occurs we need your help and active participation. I earnestly ask for it.

THE NSF/RANN FY 1975 PROGRAM
FOR
GEOTHERMAL RESOURCES RESEARCH AND TECHNOLOGY

Paul Kruger
National Science Foundation
Washington, D.C.

The NSF program for geothermal resource research and technology is a component of the Research Applications Directorate mission to serve as a bridge linkage between the Foundation's support for research applied to national needs (the RANN program) and the utilization of research results in the national economy. The specific goal of the NSF geothermal program is the rapid development by industry of the nation's geothermal resources that can be demonstrated to be commercially, environmentally and socially acceptable as alternate energy sources. NSF, as the lead agency for the federal geothermal energy research program, is expediting a program which encompasses the objectives necessary for significant utilization. These include: acceleration of exploration and assessment methods to identify commercial geothermal resources; development of innovative and improved technology to achieve economic feasibility; evaluation of policy options to resolve environmental, legal, and institutional problems; and support of experimental research facilities for each type of geothermal resource. Specific projects in each of these four objective areas are part of the NSF program for fiscal year 1975.

I. INTRODUCTION

Geothermal energy is vitally needed as an alternate source of energy in the United States. The National Science Foundation is embarked on an aggressive research and advanced technology program as part of a national effort to assist industry in the development of geothermal resources. The goal of the NSF/RANN program for geothermal energy research and technology is the development, at the earliest feasible time, of those applications of geothermal resources that can become economically competitive and environmentally acceptable as alternate energy sources in the national economy.

Although the magnitude of potential power production from geothermal energy is disputed by many competent earth scientists, the resource base is uniformly agreed to be quite vast. In the United States the total generating capacity of electric power from geothermal energy is only some 400 MW, considerably less than that from one modern nuclear power plant. In fact the 1000 MW generating capacity of electric power from geothermal resources over the entire world is just about equal to that of one such plant.

If the potential resource base of geothermal energy is so vast, why has not a greater utilization occurred? If we are to develop our national resources of geothermal energy to succeed in making a significant contribution to the Nation's energy supply, we must find a solution to this enigma.

The solution is complex. It involves factors which span the entire spectrum of the geothermal energy cycle from exploration to utilization. The answer may lie not so much with the magnitude of the potential resource, but more with our ability to extract, convert, and utilize commercial quantities of geothermal energy in an economic and environmentally acceptable manner.

The spectrum of the geothermal energy cycle is complex. Geothermal resources come in many forms, sizes, and shapes. Problems occur, also in many forms, sizes, and shapes. They include:

- (1) The need for reliable surface exploration methods to locate subsurface concentrations of geothermal heat, especially where natural surface manifestations are lacking.
- (2) The high cost of drilling deep exploratory holes in areas suggested by surface reconnaissance, especially in hard-rock, high-temperature geologic formations.
- (3) The need for adequate evaluation of potential reservoirs to ensure sufficient deliverability and reserves to warrant the capital investment in a power plant.
- (4) The need for optimum utilization for both electric power and nonelectric power applications, consistent with the wide variation in geothermal resource characteristics.
- (5) The concern for proper environmental, economic, legal, and institutional controls in the development and utilization of geothermal resources.

A program to address these problems clearly requires a comprehensive and coordinated national effort by both industry and government, and it is the basic objective of the NSF/RANN program in Advanced Geothermal Energy Research and Technology. To ensure that the many aspects of the geothermal energy cycle are adequately investigated, the RANN program has been organized in four major program categories:

- (1) Resource Exploration and Assessment
- (2) Advanced Research and Technology
- (3) Resource-Type Research Facilities
- (4) Environmental, Legal, and Institutional Aspects

The objectives of these categories are, respectively:

- (1) To provide technology for the exploration and assessment of potentially-commercial geothermal resources.

- (2) To develop methods for efficient extraction and conversion to bring each type of geothermal resource into commercial fruition.
- (3) To support the experimental research facilities needed to test the technologies and evaluate problems specific to each type of geothermal resource.
- (4) To evaluate policy options to resolve key environmental, legal, and institutional problems to minimize delay in the technology utilization.

II. RESOURCE EXPLORATION AND ASSESSMENT

Prospecting for natural resources below the earth's surface is at best a difficult undertaking. Although much progress has been achieved in locating oil, gas, and mineral deposits, exploration for geothermal energy involves two additional factors:

- (1) The resource itself is not a material fuel; it is concentrated deposits of heat located below the surface in the earth's crust and with or without the presence of geofluids;
- (2) As thermal energy, it cannot be transported very far and must be converted or utilized directly at the site of each reservoir. Thus the location of suitable reservoirs must match the location of suitable energy markets and transmission networks.

There are many exploratory techniques available for locating geothermal resources. They include surveys based on airborne magnetic and infrared mapping and geophysical, geochemical, geologic, and hydrologic methods. The great variability of geothermal energy deposits with respect to depth, shape, size, pressure, temperature, geofluid quality, and other parameters challenges greatly the prospector's ability to evaluate his many data taken at the surface. Great opportunity exists for innovative theoretical and field experimental methods to probe deeper and with greater precision.

Private industry, with the need to invest its exploration money prudently, seeks the high-grade vapor-dominated and high-temperature hydrothermal reservoirs in the hope of locating commercial fields exploitable with current technology. However, high-grade resources may represent only a small fraction of the total geothermal resources that could be exploited in the future with new technologies.

It is these "higher-risk" resources that need the support of the Federal government to locate them, assess their commercial potential, and develop the necessary technology for efficient energy extraction and conversion. Among these "higher-risk" resources are included the geopressed basins of the Gulf States, the deep hot dry rock formations in the western, and perhaps eastern, states, and the magmatic heat prevalent in Hawaii.

Geoscience methods to explore and assess these types of resources needs continuous improvement. A major part of the NSF program in geothermal energy research and technology is devoted to the specific objectives of:

- (1) Support of research in airborne, surface, and subsurface methods for geothermal resource exploration.
- (2) Support of research to improve geophysical, geochemical, geologic, hydrologic and other techniques for evaluating specific geothermal resources.
- (3) Support of research to develop better methods for predicting the productivity and longevity of potentially commercial geothermal resources.
- (4) Research support to the U.S. Geological Survey program for national and regional surveys of potential geothermal resources.

The NSF program expects to have well underway in FY 1975 several projects for the assessment of several types of geothermal resources. Some of these projects include:

- (1) Continuation of the geophysical assessment of the deep exploratory hole drilled to 7000 ft in a possibly hot intrusive near Marysville, Montana.
- (2) Continuation of the geophysical assessment of hydrothermal systems associated with magmatic heat sources in the Hawaiian Islands at sites selected for an exploratory drilling program.
- (3) Resource assessments of the geopressured basins in the vicinity of the Texas and Louisiana Gulf coasts.
- (4) Initiation of projects to explore the potential of various temperature - various salinity hydrothermal resources located in many of the western states. Possible states include: Alaska, Arizona, California, Colorado, Idaho, Montana, New Mexico, Nevada, Oregon, Utah, and Washington. For these resources the NSF program will not only support the technology research which might make them feasible for commercial electric power generation, but also programs for utilization of the thermal waters.

III. ADVANCED RESEARCH AND TECHNOLOGY

The NSF program in advanced research and technology encompasses the geothermal energy cycle from exploration to utilization. The need to have proved reserves has already been stressed and technology advances to aid in the assessment are needed. Technology advances are also needed even with proved reserves to make utilization of geothermal energy commercially feasible and environmentally acceptable.

Because of the variety of resource types, several methods of extraction and conversion technology may be needed. For example, in hot brine resources the feasibility of electric power production may hinge on the development of suitable down-hole pumps to prevent the brine from flashing in a binary fluid, heat exchanger system. Whereas, in hot, dry rock resources, the feasibility of electric power production may hinge on obtaining sufficient heat transfer surface in a fractured-rock formation and a suitable artificial circulation system to extract the heat economically.

Some of the specific objectives of the NSF program to support the development of the appropriate technologies for the several types of geothermal reservoirs are:

- (1) Efficient drilling and well-completion methods in high temperature geologic formations.

Drilling is presently accomplished by the type of rotary drilling employed for oil wells, using either mud or air as the drilling fluid. Drilling represents a major investment in the development of a geothermal field. Obviously, any technical improvements for drilling in geothermal environments, such as deep hot water or dry hard rock formations could result in great economic savings. Alternate drilling methods, such as turbine drilling, melting drilling, and erosion drilling, need to be investigated; none are yet commercially available.

- (2) Efficient reservoir engineering and management techniques.

An evaluation of a reservoir for deliverability, reserves, and longevity is required for optimum field development and production. Research is needed for methods to evaluate formation characteristics, with borehole measurements, production testing, and theoretical models. In some cases, economic justification for power plant construction may require by-product utilization, perhaps in the form of desalinated water, commercial minerals, and process heat.

- (3) Increased extraction efficiency.

Many geothermal resources will be found to be submarginal for economic exploitation. Perhaps there will be insufficient geofluid production to amortize a power plant of the size needed. An artificial circulation system may be required.

Perhaps there will be insufficient surface area for sufficiently rapid heat transfer from the formation to the produced fluids. Fracturing of the aquifer formation may be required.

Perhaps the deposition of silica, calcite, or other minerals may decrease formation porosity or permeability. Other stimulation techniques may be required.

Several stimulation techniques have been proposed. They include hydraulic fracturing, thermal stressing, and explosive fracturing with chemical or nuclear explosives. Each of these methods, as well as the development of artificial circulation systems, is yet undeveloped and requires considerable

research effort before any one of them will be ready for commercial utilization.

NSF is supporting studies for increased extraction efficiency. The first laboratory demonstration of heat extraction from fracture-stimulated hard rock was completed at the Stanford University geothermal laboratory. First results from the geothermal chimney model indicated a significant increase in nonisothermal heat extraction from a simulated fractured rock hydrothermal system compared to isothermal flashing of hydrothermal fluids, which is practiced at existing hot water geothermal fields. Other such studies will be supported under the NSF program during FY 1975; for example, concepts to stimulate production in dry holes drilled in zones of known geothermal steam and hot water reservoirs.

(4) Increased conversion efficiency.

It is generally accepted that hydrothermal systems with hot water at temperatures below 200°C will be more abundant relative to steam fields. Thus improved technology to utilize such low-quality thermal fluids for electric power production is urgently needed.

Many investigations are underway to seek such technologies. Several types of geothermal power plants are being considered, such as low-pressure steam turbines; binary cycle systems; and hybrid systems.

Each type requires multiple-well and gathering-line complexes to bring sufficient production to the power plant. Although research and development of such near-commercial systems are more properly within the domain of private industry, research for the development of innovative components to make them more effective, efficient, or even possible, at an early time, are well within the scope of the NSF program.

Innovative conversion systems, in which the power plant is brought to the individual well, deserves consideration. Demonstration of electricity production by a helical rotary screw expander was achieved at the East Mesa geothermal field. Continuation of this research concept is part of the NSF FY 1975 program. Perhaps there are other mobile conversion systems that can be used on an individual well basis.

(5) Increased utilization efficiency.

Planning and development of geothermal fields must consider the physical characteristics of the produced fluid, the gathering and steam-water separation facilities, the turbine and generator equipment, the cooling cycle, the well productivity and spacing, environmental impacts, and condensate disposal methods.

All this presupposes that electric power generation is the sole purpose of developing geothermal resources. It may turn out, however, that a very significant savings of fossil and nuclear fuels may be achieved by direct utilization of geothermal resources for its heat, water, and mineral content.

Hydrothermal fluids with insufficient temperature or enthalpy for commercial power production might be used as water and mineral sources and for space and process heating. However, since major interest in geothermal energy lies in the production of electric power, the combined or total utilization may help make geothermal fields that are submarginal in power production economically feasible. Research in methods for stimulation of geothermal resource utilization in all forms is thus an important part of the NSF geothermal program.

(6) Environmental control technology

This area of advanced research and technology has become a significant aspect of advanced technology in the last decade. It is covered in the section on environmental, legal and institutional aspects.

IV. RESOURCE-TYPE RESEARCH FACILITIES

There comes a time for each type of geothermal resource when research has been taken to an important milestone, when the resource assessment has led to a promising site, when the technology concepts have been taken beyond the drawing board and laboratory, and when a system for extraction and conversion (or its components) must be tested under actual field operating conditions.

Suitable electric power generating systems at a size consistent with the estimated reservoir capacity and utility needs must be demonstrated under geothermal operations which are economically feasible, environmentally acceptable and conform to federal, state, and local regulations.

Geothermal resources are needed to provide fluid production on a continuous basis for such demonstrations. They are needed to test components, to evaluate nonelectric utilizations, to monitor potential environmental impacts, and to test environmental control systems.

Some geothermal resources are also needed to test the very important aspect of resource feasibility itself. Some types of resources, such as high temperature-low salinity, are very close to commercial exploitation. Other types, such as hot, dry rock, require much research and technology before they can be considered close to commercial exploitation.

All of these reasons lead to a need for geothermal research facilities by resource type. The NSF program envisions a series of resource-type research facilities which span both the spectrum of state of development of geothermal type and state-of-the-art of its exploitation. Two such studies, seeking suitable sites for research facilities, are currently being supported by the NSF program.

The scope of work appropriate to each type of geothermal resource will vary widely. The most advanced type is the dry steam field, exemplified by the Geysers in California. The production of electric power at this field is well established; and yet sufficient need for improvement and sufficient problems still exist to consider a research facility at this resource type.

The hot brine deposits of the Salton Sea for many years have been considered to have great commercial potential. Yet the breakthrough needed to handle this fluid for power production has not yet been achieved. A research facility for this geothermal resource is urgently needed both for demonstration of power production and as a production source for technology testing. It has been noted on several occasions that any technology that works with hot brines will work readily with any other type of geofluid.

There are many potential sites for a research facility at moderate temperature and low to moderate salinity reservoirs. Several states have already been named that have such resources. The NSF program envisions the funding of one or more such research facilities under a research team of university, industry, utility, and state and local regulatory agencies for developing a comprehensive research program appropriate for the specific geothermal resource.

Similar programs are sought for geopressured basin resources, magmatic resources, and dry, hot rock resources. A major effort of the FY 1975 NSF program is planned for these resource-type research facilities.

Some of the benefits which are likely to result from this phase of the program include:

- (1) Economic data for geothermal production systems and components which meet technical and environmental standards.
- (2) Industrial operating experience in reservoir engineering and management.
- (3) Early operational experience with demonstration power plants which may hopefully serve as Unit No. 1 of commercial field development.
- (4) Operational characteristics and potential of each type of geothermal resource.
- (5) Trained engineers, technicians, analysts, and managers from industry with early field and power plant development experience.
- (6) The basis for satisfying environmental and institutional requirements for geothermal resource utilization.

V. ENVIRONMENTAL, LEGAL, AND INSTITUTIONAL ASPECTS

A major component of the NSF geothermal research program is focused on the environmental, legal, and institutional aspects of geothermal resource utilization.

The problems are complex and involve public acceptance, vested interests, historical precedents, existing regulations not directly resulting from geothermal operations, overlapping jurisdictions, and economic factors.

These problems are often more difficult to resolve than are engineering obstacles and they may in the long run be the major constraints to an orderly, rapid, development of geothermal resources.

The solution to such problems may require broad public interaction, changes in laws and regulations, and perhaps changes in traditional investment and marketing procedures.

Many lists of real, potential, and imaginary environmental impacts have been published over the past few years. Potential environmental impacts have been identified as gaseous emissions, liquid waste disposal, and geophysical effects, among others. What is needed now are not more lists, but objective evaluations of the actual severity and magnitude of the important potential environmental impacts and baseline data and advanced technology for monitoring the potential impacts and controlling the actual hazards.

In addition to the extensive capability of the environmental resources staff in the RANN program, the NSF geothermal program seeks competent investigators to undertake research projects to evaluate these impacts and to develop methods for monitoring and control where needed. To initiate this phase of the program NSF will support a Workshop on Environmental Aspects of Geothermal Resources Development. The results of this workshop will be widely distributed to ensure its maximum utilization by industry and regulatory agencies.

Evaluation of the legal aspects of geothermal energy is another major objective of the NSF FY 1975 program. Many basic questions remain unresolved; such as the definition of a geothermal resource, its classification as water, mineral, or energy, application of various tax incentive policies, effects of alternate bidding and leasing arrangements, investment assistance to promote early exploration, and simplification of regulatory and licensing procedures at three levels of government - federal, state, and local. The NSF program will also support a workshop to investigate the critical legal constraints inhibiting the commercial utilization of geothermal resources. The results of this workshop will also be distributed rapidly and broadly to provide a general basis for the resolution of these problems as recommendations for administrative and legislative actions.

Institutional problems involve social and economic questions. They involve land use planning, especially complex when geothermal resources span Federal, State and private lands. They involve capital investment, especially when private investment institutions may be reluctant to undertake high-risk, long-delay time geothermal projects. They involve interindustry arrangements, especially when multipurpose utilization is needed to support economic development. And they involve multigovernment arrangements, especially in the realms of regulation, licensing, and utilization.

Research is needed in each of these problem areas. The NSF program is supporting intergovernmental programs to evaluate and incorporate the impact of geothermal development in local and regional planning. The objective of these programs is to provide state and local regulatory agencies with sufficient expertise in geothermal technology to avoid major regulatory conflict

and to smooth the way for acceptable development and utilization of geothermal resources on a local and state-wide basis.

VI. THE NSF FY 1975 BUDGET

To accomplish this many faceted advanced research and technology program in geothermal energy, the NSF has budgeted for FY 1975 a total of \$22,300,000, divided among the four program objectives as follows:

Resource Exploration and Assessment	\$ 3,000,000
Advanced Research and Technology	7,500,000
Resource-type Research Facilities	9,500,000
Environmental, Legal, Institutional Aspects	<u>2,300,000</u>
Total	\$22,300,000

The FY 1975 budget represents a marked challenge to accelerate the NSF program supported by the FY 1974 budget of \$3,700,000. The National Science Foundation actively seeks research proposals in each and all of these program objectives. The Program Managers of the Advanced Geothermal Energy Research and Technology section are ready to assist qualified researchers in obtaining NSF support.

GEOTHERMAL RESEARCH AND DEVELOPMENT PROGRAM
OF THE U. S. ATOMIC ENERGY COMMISSION

Louis B. Werner
U. S. Atomic Energy Commission
Washington, D. C.

Within the overall federal geothermal program, the Atomic Energy Commission has chosen to concentrate on development of resource utilization and advanced research and technology as the areas most suitable to the expertise of its staff and that of the National Laboratories. The Commission's work in geothermal energy is coordinated with that of other agencies by the National Science Foundation, which has been assigned lead agency by the Office of Management and Budget. The objective of the Commission's program, consistent with the goals of the total federal program is to facilitate, through technological advancement and pilot plant operations, achievement of substantial commercial production of electrical power and utilization of geothermal heat by the year 1985. This will hopefully be accomplished by providing, in conjunction with industry, credible information on the economic operation and technological reliability of geothermal power and use of geothermal heat.

The Atomic Energy Commission's program for development of geothermal energy was first funded in 1973 at a level of \$4.7 million. Funding for the current government fiscal year is \$10.8 million.

At the outset, the Commission's program was developed largely through its National Laboratories. On June 18, 1974, a Geothermal Power Development Conference was held in Berkeley, California, for the purpose of describing the program as currently formulated and to solicit comments, recommendations and criticisms regarding it. Results of this meeting showed, in part, that much closer communication with and involvement of industry must be achieved, and that the Commission's program should be more responsive to ongoing industrial activities. It is hoped that the NSF-sponsored Conference on Research for the Development of Geothermal Energy Resources will assist in achieving these goals.

In addition, informal workshops are being planned on specialized topics, and a solicitation of interest is being prepared relating to joint projects with industry which would involve both industrial facilities and knowhow.

The Commission's resource utilization program is directed toward economic utilization of geopressured, convective hydrothermal, and dry geothermal resources for production of power and for nonelectric uses. A program concept definition study currently is underway to identify prospects for economical use of geothermal heat for nonelectric uses and to define further technical development which may be required. Advanced research and technology studies are planned in the areas of advanced drilling, reservoir modeling, downhole instrumentation development, low-temperature heat conversion, heat exchanger development and materials development. In order to better define the role of geothermal energy in relation to competing resources and to evaluate cost/benefit aspects of exploitation of various resource types, plant designs and development strategies, an economic modeling study is being performed. Also, a geothermal utilization systems analysis has been started for the purpose of providing a milestone and decision-point-oriented national activities network. It is hoped by this means to facilitate the formulation of quantitative goals and milestones for the government-sponsored aspects of the national program and to ensure that results needed to reach national goals are achieved in a timely fashion. It is apparent that successful development and application of these objectives can only be achieved with the fullest support and participation by industry, and the AEC wishes to reemphasize the importance it attaches to incorporation of industry in all phases of its geothermal program.

The United States Atomic Energy Commission's work in geothermal energy is coordinated with that of other agencies through the National Science Foundation which has been assigned lead agency by the Office of Management and Budget. The objective of the Commission's program, consistent with the goals of the total federal program is to facilitate, through technological advancement and pilot plant operations, achievement of substantial commercial production of electrical power and utilization of geothermal heat by the year 1985. This will hopefully be accomplished by providing, in conjunction with industry, credible information on the economic operation and technological reliability of geothermal power and use of geothermal heat.

Inasmuch as construction of commercial utilization facilities is obviously a voluntary decision on the part of industry the strategy adopted by the AEC is to attempt to stimulate that decision through performance of essential research and development work particularly in areas where industry lacks near-term profit motivation or lacks appropriate staff and facilities to perform such work.

It is intended to develop information in cooperation with industry, in part, as an adjunct to industrial activities having similar overall objectives, but principally as a means for advancing geothermal utilization technology beyond that currently available. The strategy adopted for achievement of program objectives thus involves cooperative demonstration programs with industry in addition to longer term research and development work.

At the outset the AEC program was developed largely through activities of its staff and the National Laboratories beginning in late 1972.

The AEC program finally came into being in December 1973 after the passage by Congress of legislation which provided funding at a level of \$4.7 million for geothermal work and the apportionment of these funds by the Office of Management and Budget.

In December 1973 the staff began laying plans for formally integrating the AEC program with industrial and other nonfederal interests. As a first step, the staff proposed that public notice be given of the conduct of AEC's Research and Development activities in geothermal energy and that there be held a public information meeting for the purpose of describing the program as then formulated and soliciting comments, recommendations and criticisms regarding its content. Such a notice was eventually published in the Federal Register June 11, 1974 and a meeting known as the Geothermal Power Development Conference was held on June 18, 1974 in Berkeley, California. Registered attendance was in excess of 200 people.

The Proceedings of that conference have been published and can be obtained from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia, at a nominal cost.

Insofar as the purposes of the geothermal conference at the California Institute of Technology correspond with the purposes of the Berkeley Conference it may be of interest to summarize briefly the results of the Berkeley meeting, and the responses to the notice published in the Federal Register.

Each attendee at the Berkeley meeting was asked to respond to a questionnaire. The total number of respondents was 17, and the composition of these respondents according to affiliation was as follows:

(1)	Energy Companies	7
(2)	Engineering Companies	3
(3)	Universities	3
(4)	Utilities	2
(5)	Public Power Groups	1
(6)	State Government	1

The major comments received were as follows:

- (1) 14 respondents described the Berkeley meeting as useful or very useful.
- (2) 11 respondents urged similar meetings in the future, most commonly suggesting semiannually or annually.
- (3) 10 respondents emphasized the need to involve industry much more closely in the design and implementation of the program.
- (4) 9 respondents stated that they would consider participating in AEC projects on a cooperative, joint support basis.

- (5) 2 respondents commented adversely on the apparent duplication between AEC and NSF programs.
- (6) One respondent stated AEC had a serious credibility problem in the sense that AEC's objective appeared to be to establish a geothermal TVA.

In addition a number of miscellaneous comments were received:

- (1) 2 respondents urged greater involvement of universities in the program.
- (2) 2 respondents recommended that greater attention be given to nonelectric applications.
- (3) One respondent emphasized the need to resolve the institutional problems inhibiting geothermal energy.
- (4) Several respondents identified particular areas of R&D they felt needed attention.

For the most part we were gratified by this response and agree that many of these suggestions have merit. I would like to call attention to a few recent actions taken in the government programs which are related to some of those comments.

First, the need for closer coordination of the federal agency programs is being achieved through the Interagency Panel for Geothermal Energy, chaired by the National Science Foundation as lead agency. This Panel is now meeting frequently and shows good promise of being an effective instrument for program coordination, and dealing with matters such as duplication of effort among government agencies.

Second, industry has been requested to participate in top level review and planning of federal geothermal programs through establishment of a blue ribbon Geothermal Industry Liaison Panel, the members of which have been invited by the National Science Foundation in consultation with the Interagency Panel to serve in this capacity. It is believed that this will be a very important mechanism for industrial involvement in the design and implementation of government programs.

Third, informal workshops are being planned by AEC, NSF, and the U. S. Geological Survey to provide in-depth evaluations of specialized technical topics. AEC has tentatively scheduled a workshop on energy conversion systems for November 4-5, 1974. It is proposed to invite a limited number of industrial and government people who are actively working in power cycle development and applications to participate in a review of current status of this field, of development work in progress, and needs for additional research and development.

Fourth, a number of informal visits to industries have been made during August and September by representatives from the three agencies: NSF,

Department of Interior, and AEC. The purpose is to become better familiar with and to evaluate the status of industrial work and interests in geothermal energy as it relates to the role which federal programs should fill in the national effort.

Fifth, with respect to technical and operational aspects of our program, the AEC has been reexamining the objectives and general approach of its program particularly as it relates to ongoing industrial activities in order to ensure the most effective contribution to the national program. As a result of this reevaluation there may be other modifications to the program in the near future.

The impetus for these actions has, of course, come from a number of sources, but it is fair to state that constructive criticism and suggestions such as those we received from the Conference participants have been of great benefit in reassessing our objectives.

We have reason to hope, I believe, that the NSF-sponsored Conference on Research for the Development of Geothermal Energy Resources will further assist in achieving these goals.

I would like to turn now to a discussion of the AEC's technical program. This will be brief inasmuch as there will be detailed presentations from members of the National Laboratories in which three of the principal programs will be described.

The geothermal research and development program funded by the federal government is generally described under four categories: (1) Resource Exploration and Assessment; (2) Environmental, Legal and Institutional; (3) Resource Utilization; and (4) Advanced Research and Technology.

Within the overall federal program the Atomic Energy Commission has chosen to concentrate on development of resource utilization and advanced research and technology as the areas most suitable to the experience and expertise of its staff and that of the National Laboratories.

This is not to suggest that the first two categories of the program are in any way less important, but only that it is believed that the greatest contribution by AEC can be made in the categories of resource utilization and advanced research and technology.

The principal objectives of the geothermal resource utilization program are as follows:

- (1) Develop economic utilization systems and components for generating electric power and for providing heat for other purposes such as space heating and cooling;
- (2) Demonstrate these systems and components in test facilities;
- (3) Gain experience in reservoir assessment and management;

- (4) Acquire operational and cost experience with several different types of utilization systems and resources;
- (5) Develop trained geothermal engineers and technicians; and
- (6) Participate with industry in research and development leading to early industrial exploitation of geothermal resources of all types.

The program encompasses the major types of geothermal resources, namely hot dry rock, convective hydrothermal and geopressed systems, and near-normal or tectonic heat-gradient formations.

Programmatic responsibility for each of these resource types has been assigned to one of the AEC Laboratories. These assignments and the fiscal year 1974 and 1975 budgets are shown in Table 1.

In addition to resource utilization programs, advanced research and technology development common to all geothermal systems will be required for full development of the potentialities of the several types of geothermal energy resources. The ultimate goal of this effort is to solve technical problems inhibiting the full commercial utilization of geothermal resources. The objectives of the advanced technology program are to:

- (1) Develop new methods for drilling in high temperature "hostile" geothermal environments rapidly and economically;
- (2) Develop or test component hardware for handling and utilization of geothermal fluids, e.g., advanced heat exchanger designs.
- (3) Develop improved methods for recovery of geothermal fluids and for converting the energy into electrical power and other applications;
- (4) Design new and improved equipment, including downhole instrumentation capable of operation at high temperatures and in corrosive fluid media.

The programs supported by the AEC in this area and the fiscal year 1974 and 1975 budgets are shown in Table 2.

There will be presentations at this Conference on hot dry rock and convective hydrothermal systems, so perhaps a few comments would be appropriate concerning some other aspects of the program.

We have become quite interested in the possible uses of geothermal heat for nonelectric purposes. It is well known that geothermal water has been used successfully for many years for heating homes in Iceland, Hungary, France, and to a more limited extent the United States. There is also extensive use of geothermal energy in other countries for heating greenhouses, and to some extent for industrial process heat. Two complementary studies on nonelectric uses in which the AEC is participating are concurrently underway. One of these is sponsored by the NATO Committee on Challenges of Modern

Society. These studies can be expected to identify promising applications and areas for further technological development. A number of examples of thermal energy uses have been identified as shown below.

Residential and Commercial:

- (1) Space heating and cooling
- (2) Domestic water (potable, hot/cold utility)
- (3) Waste treatment (disposal, bioconversion)
- (4) Refrigeration
- (5) Deicing
- (6) Total energy systems (cascade utilization)

Agriculture and Related Areas:

- (1) Crops (greenhouses, hydroponics, heated soil)
- (2) Animal husbandry (cattle, pigs, chickens)
- (3) Aquatic farming (fish rearing)
- (4) Processing of agricultural products (drying)

Industrial Processes:

- (1) Chemical production
- (2) Pulp treatment
- (3) Mining (heat, water)
- (4) Drying (cement, diatomaceous earth)
- (5) Water desalination/distillation
- (6) Mineral recovery from geothermal brines

In each of these cases the technology to be assessed or developed would depend upon features of the specific resource being considered and the possible applications in that locality. In general, areas of technology development could include: thermal energy transport and storage; heat exchange systems; fluid/mineral separators; low temperature turbines; and heat pumps. In addition there would be areas of development peculiar to the specific applications including interactions with other energy systems.

If the program definition study is favorable, selected projects will be funded during FY 1975.

In order to better define the role of geothermal energy in relation to competing resources, an economic modeling study is being performed. This model will evaluate cost/benefit aspects of exploitation of various resource types, plant designs and development strategies.

There are two principal objectives: (1) to define the role of geothermal energy in relation to competing resources and (2) to further the optimum development of geothermal energy. In accomplishing these objectives, a model will be constructed which will provide an economic basis for performing benefit-cost analyses of Government-sponsored research and development programs. The model will also provide the basis for economic comparisons between geothermal power programs and programs in other energy technologies.

During this year the program will be concerned with (1) the completion of deterministic economic cost models and sensitivity analyses for all geothermal resource types, (2) a macroeconomic (logistics) analysis for geothermal energy, (3) development of an economic optimization model for geothermal energy development, and (4) an analysis of the national benefits of geothermal energy.

In addition, a geothermal systems analysis is being performed for the purpose of providing a milestone and decision-point oriented national activities network. It is hoped by this means to facilitate the formulation of quantitative goals and milestones for the government-sponsored aspects of the national program, and to ensure that results needed to reach national goals are achieved in a timely fashion. It is apparent that successful achievement of these and other program objectives can only be accomplished with the fullest support and participation by industry, and the AEC wishes to reemphasize the importance it attaches to involvement of industry in all phases of its geothermal program.

Table 1. Resource utilization program assignments and budget

Resource	Laboratory	FY 1974 (\$1,000)	FY 1975 (\$1,000)
HDR	Los Alamos Scientific Laboratory	2,970	3,800
HT/LS	Lawrence Berkeley Laboratory	800	1,000
HT/HS	Lawrence Livermore Laboratory	420	2,200
MT/LS	Idaho National Engineering Laboratory	245	950
Geopressured	Lawrence Livermore Laboratory	25	600
Near-Normal Gradient	Los Alamos Scientific Laboratory	0	100
		<hr/> 4,470	<hr/> 8,650

Table 2. Advanced research and technology budget

Program	FY 1974 (\$1,000)	FY 1975 (\$1,000)
Advanced drilling	0	400
Heat exchanger development	0	250
Low temperature heat conversion	250	250
Nonelectric uses	35	400
Materials development	0	100
Other	0	450
Economic study	200	300
	<u>485</u>	<u>2,150</u>
Grand total (approximate)	5,000	10,800

OVERVIEW OF RECLAMATION'S GEOTHERMAL PROGRAM
IN IMPERIAL VALLEY, CALIFORNIA

Martin K. Fulcher
U. S. Bureau of Reclamation
Boulder City, Nevada

The Bureau of Reclamation is presently involved in a unique Geothermal Resource Development Program in Imperial Valley, California. The main purpose of the investigations is to determine the feasibility of providing a source of fresh water through desalting geothermal fluids stored in the aquifers underlying the valley. Significant progress in this research and development stage to date includes extensive geophysical investigations and the drilling of five geothermal wells on the Mesa anomaly. Four of the wells are for production and monitoring the anomaly, and one will be used for reinjection of waste brines from the desalting units. Two desalting units, a multistage flash unit and a vertical tube evaporator unit, have been erected at the East Mesa test site. The units have been operated on shakedown and continuous runs and have produced substantial quantities of high-quality water. Bechtel Corporation of San Francisco, California, is assisting Reclamation in the evaluation of geothermal desalting. Later program stages will evaluate the feasibility of producing large quantities of product water along with the generation of electric energy and investigation of mineral recovery. Reclamation has a unique test facility on the East Mesa of Imperial Valley that is available as a field laboratory for selected scientists for testing and research under actual field conditions with producing geothermal wells.

I. INTRODUCTION

The Bureau of Reclamation is presently involved in a unique Geothermal Resource Development Program in Imperial Valley, California. The main purpose of the investigations is to determine the feasibility of providing a source of fresh water for augmentation of the Lower Colorado River system through desalting geothermal fluids stored in the aquifers underlying the valley. Water shortages in the foreseeable future are very probable, unless some form of river augmentation is accomplished.

The Bureau's research and development program is investigating the feasibility of desalting mineralized geothermal fluids and delivering the fresh water to the Colorado River system to help meet the future needs of the arid Southwest. The addition of large amounts of high-quality water would also counteract the serious problem of increasing salinity of the river.

The advantage of obtaining fresh water from geothermal sources by desalting is that the application of heat, so essential for distillation processes, is not required from external sources. The earth yields this required component naturally in the form of hot fluids under pressure.

Geothermal deposits are one of the nation's relatively untapped resources. They could provide electric energy, fresh water, and possibly mineral byproducts without the associated air pollution so prevalent with other methods of energy, water, and mineral production.

II. GEOLOGICAL HISTORY

The Colorado River for millions of years has gouged the landscape of the Southwest, leaving scenic canyons such as the Grand Canyon, carrying trillions of tons of sediment to the Gulf of California. Through the centuries, the river has spilled sporadically into the Imperial Valley, building a delta thousands of feet deep. The periodic floods have saturated the delta with water, estimated at several billion acre-feet. This water is stored in the subterranean strata of Imperial Valley as a latent resource awaiting man to release part of it to serve the Southwest. This structural feature filled with saturated sediments is called the "Salton Trough."

The Salton Trough lies astride the East Pacific Rise, a primal fault from which molten rock from the earth's mantle provides a mechanism whereby the sediments in the trough are heated to high temperatures by abnormal heat flow.

III. GEOTHERMAL RESOURCES

It is possible to tap the heat in saturated rocks by drilling geothermal wells. Geothermal wells are drilled routinely by qualified drillers in areas of high heat flow in many parts of the world. Geothermal reservoir engineering technology is presently in its infancy, but techniques for the exploration of geothermal resources are being improved constantly.

Remarkable developments in the use of geothermal resources are to be expected worldwide in years to come. Countries in which geothermal developments are underway include the United States, Japan, Russia, Iceland, New Zealand, Italy, and Mexico. The Imperial Valley area of southern California has one of the greatest known potentials for a successful geothermal development in this country.

The Bureau of Reclamation began long-range planning in 1968 on Reclamation withdrawn lands in Imperial Valley by providing financial aid to the University of California at Riverside, which had been studying the Geothermal resource in Imperial Valley since 1964. Reclamation became physically involved in 1971 by drilling on several geothermal anomalies, which substantiated earlier studies and provided the information needed to proceed with further research.

The results of the shallow drilling program, along with seismic ground-noise studies, gravity studies, and lithologic studies of other deep wells in the area, indicated that the first deep geothermal test well should be located near the center of the "Mesa anomaly." The well designated Mesa 6-1 was begun in June 1972 and completed in August 1972 to a depth of 8030 feet. Figure 1 shows the location of the Bureau facilities in southern Imperial Valley and the location of the East Mesa anomaly. Also shown is the Cerro Prieto steam field in the Mexicali Valley in Mexico.

Mesa 6-1 has a bottom hole temperature of 400°F. Under throttled flow conditions, fluid emerges at the surface at about 300°F.

After the fluid is forced to the surface by the temperatures and pressures from within the earth, it is directed to the cyclone separator, where the steam and liquid are separated and passed into the desalting units. Automatic pressure and level controllers at the separator allow the operator to retain complete and precise control of the steam and liquid as they pass into the desalting plants.

Cooperative studies with the Geological Survey and the University of California at Riverside have determined seismic activity and characteristics of the geothermal fluids. Instruments for measuring subsidence have been installed in selected areas. A subsidence level network has been established over the valley, and a seismic network covers a large part of the valley. The Bureau of Mines is actively involved by conducting research on the mineral content of the geothermal fluids. The Bureau of Land Management and State agencies of California are also involved with our program. The Department of Agriculture Research Service has established a test irrigation development at the East Mesa test site to investigate the use of desalted geothermal water for irrigation.

A major environmental safeguard is the 38-acre-foot capacity brine holding pond. The pond is lined with a 10-mil polyvinyl chloride plastic sheeting to prevent waste saline water produced by the well from infiltrating the local shallow ground-water table.

IV. DESALTING PLANTS

Testing is presently underway on the desalting plants. Installed at the test site is an experimental multistage flash (MSF) desalting unit and a vertical tube evaporator (VTE) unit. These units were built under contract with the Office of Saline Water specifically for research on developing fresh water from geothermal resources.

Both units rely on the effect of condensing steam from a hot, boiling fluid to produce distilled or product water. The major expense in producing product water from brine by distillation is in the heating of the salty water by external means in other types of distillation desalting processes. In the desalting of geothermal fluids, this major expense is unnecessary because the fluid is already heated from deep within the earth, where nature has provided an almost unlimited source of heat energy.

The desalting process is explained in more detail elsewhere in this proceedings (Suemoto and Mathias).

This "first-ever" project is planned to determine economical methods of desalting geothermal fluids and to provide data for the design of larger desalting plants. In the chemical laboratory at the test site, many of the problems associated with geothermal desalting are being analyzed. Although there is much experience in desalting seawater, geothermal water has unique characteristics. Because of the differences, significant research must be accomplished to determine exactly how geothermal fluids react to desalting equipment. The corrosion and scaling tendencies on vessels and heat exchanger surfaces must be determined. Problems with equipment, which in many cases cannot be anticipated in advance, must be solved. A contract is presently underway with a consulting firm to independently analyze the desalting process and make recommendations on improving the system.

V. ADDITIONAL DEVELOPMENT

A second deep test well, designated as Mesa 6-2, was drilled during the summer of 1973 to a depth of 6005 feet on the Mesa anomaly. It is located 1475 feet west of Mesa 6-1. Mesa 6-2 is cased to a depth of 5951 feet with the bottom 500 feet slotted. Temperature surveys show the bottom hole temperature to be 369°F, and the wellhead temperature of the flowing fluid is about 300°F.

To maintain continuity of operation, the brine produced during the desalting process will be reinjected into the producing geological formations. While the disposal capability of the lined pond will permit limited testing, an injection well will be essential for continual operation of the desalting units.

Three additional geothermal wells have been recently completed. One will be used for reinjection of waste brines from the desalting units, and the other two will be used to obtain additional data to further define the Mesa anomaly.

Geothermal well Mesa 5-1, located about one and one-half miles northeast of Mesa 6-1, was drilled to a depth of 6000 feet. Downhole temperature surveys indicate a bottom hole temperature of 319°F. The fluid reaches the ground surface at a temperature of about 268°F at a flow rate of 360 gallons per minute. Since this well has slightly lower downhole temperatures than the other wells, it is scheduled for use as an injection well. It is expected that the colder and heavier injection water will flow down the well by gravity and may not require pumping.

Well Mesa 8-1 is located about one-half mile southeast of the facilities at Mesa 6-1. The bottom temperature was measured at 356°F. Preliminary tests indicate a maximum flow of about 1 cubic feet per second. Figure 2 shows the well blowing soon after drilling.

Well Mesa 31-1 is located near the north edge of the Mesa anomaly about two miles north of Mesa 6-1. It was completed on June 24, 1974. Temperature, pressure, and flow testing is now underway.

Twenty-four shallow temperature test holes 300 to 1000 feet deep were drilled during the winter of 1973-1974 to obtain heat flow data and monitor the anomaly.

Although the environmental impact is expected to be minimal with geothermal development, all environmental aspects will be thoroughly analyzed. Satisfactory methods of controlling gas emissions and disposal of waste materials will be studied. Environmental impact statements have been filed on the research and development activities.

Subsidence could become a serious problem when large quantities of ground water are extracted unless the producing aquifers are repressurized. Salton Sea water and ocean water are possible sources of replacement fluids. Investigations are continuing in this regard. Delivery points for product water are being analyzed to determine the most practical location.

The drilling and testing that have been done in the Mesa anomaly are the beginning of the research and development or first stage. This seven-year program will include field surveys and drilling and production testing, including the development of new technology from the first desalting test units. This stage will culminate in the construction of a larger prototype desalting plant with a capacity of 2 to 5 million gallons per day.

VI. FUTURE INVESTIGATIONS

Later program stages will progressively evaluate the feasibility of producing large quantities of high-quality water along with the generation of electric energy. Investigation of mineral recovery will be an important part of the program. It is anticipated that a multipurpose development will result in lower-cost products than single-purpose development. Reclamation is working with the Department of Agriculture on the experimental irrigation of crops common to Imperial Valley with high-quality desalted water. Use of this water will require a highly efficient irrigation system such as trickle deliveries.

Under a large-scale development, the desalted water could be delivered to several points along the Colorado River such as Imperial Reservoir or Lake Mead behind Hoover Dam. Lake Mead is the highest and most costly point of delivery in the Lower Basin, but would assure the greatest benefits for storage and regulation.

VII. CONCLUSIONS

Research to date clearly indicates that the geothermal resources underlying Imperial Valley offer considerable promise that someday more and better water can be developed within the Colorado River Basin for use in the Colorado River system. The geothermal program, not only in southern California, but possibly in other western states as well, could provide a solution to present-day water problems in both quantitative and qualitative terms.

In view of the present energy shortages, it is becoming increasingly important that the necessary steps be taken to begin capturing the energy from the latent geothermal resource. A multipurpose project could maximize the geothermal development by supplementing the production of high-quality water with the generation of electrical energy and mineral recovery. It is estimated that geothermal steam in Imperial Valley could produce several times the electric power capacity of Hoover Dam's generators.

Several private companies have proposed to install test units at the site, such as heat exchangers, downhole pumps, unique desalting devices, scale testing units, and various types of power generators. Recently, a private research and development company set up a scaling test unit at Mesa 6-1 to obtain data under actual geothermal field conditions. Others have also requested permission to set up test units.

Reclamation has a unique test facility on the East Mesa of Imperial Valley that is available as a field laboratory to selected scientists for testing and research under actual field conditions with producing geothermal wells.

As shortages continue to mount, it is becoming increasingly important to proceed on an orderly plan of development to help meet the water needs of the Lower Colorado River Basin, now and in the future. Input from this spectrum will help to assure that all the potential uses of the geothermal resource are fully evaluated and can be put to their maximum beneficial use for the good of mankind.



Fig. 1. Location of Bureau of Reclamation facilities, East Mesa anomaly, and Cerro Prieto steam field (photo by Bureau of Reclamation, U. S. Department of the Interior)

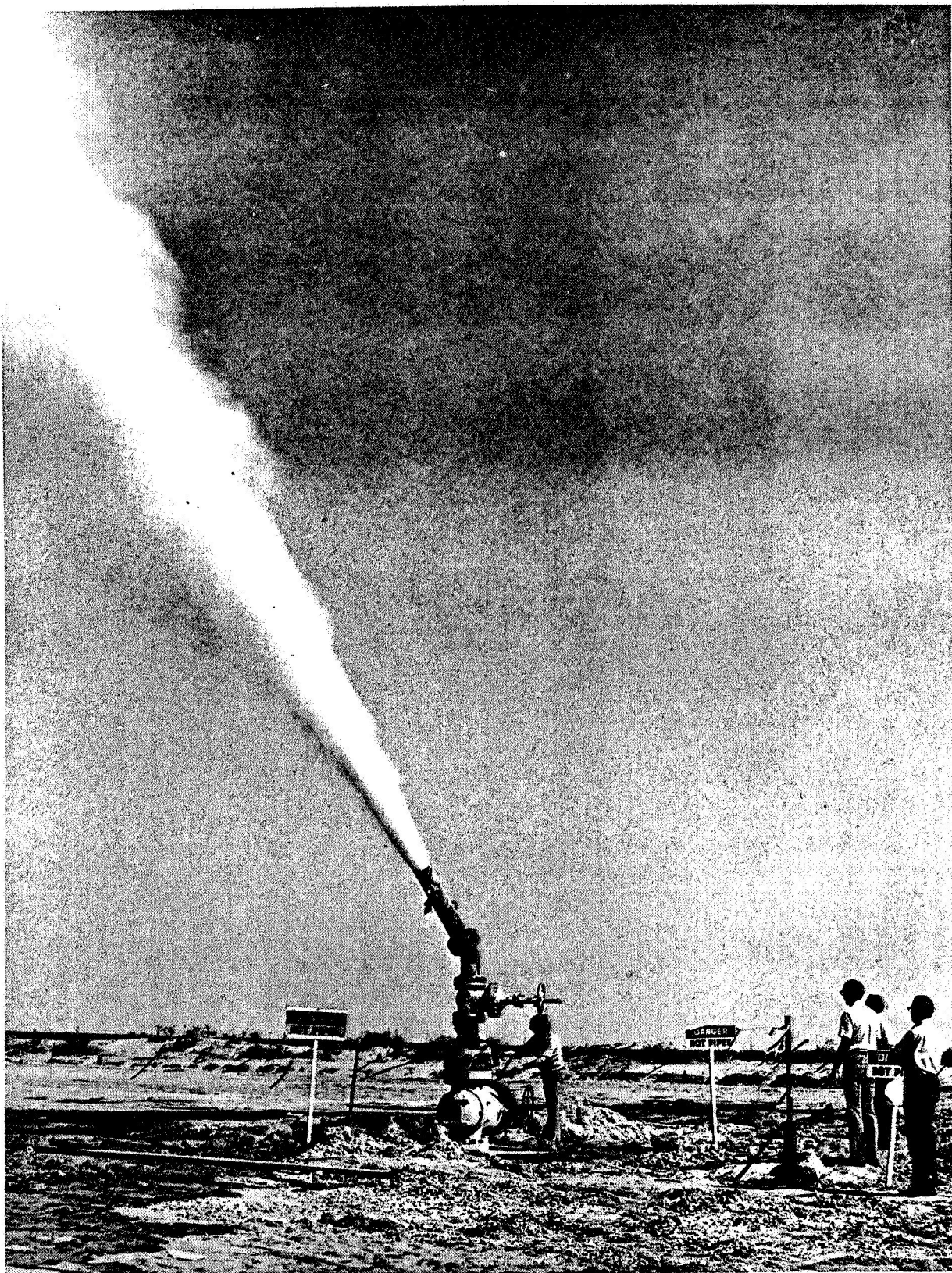


Fig. 2. Well at Mesa 8-1 blowing soon after drilling (photo by Bureau of U. S. Department of the Interior)

THE U.S. GEOLOGICAL SURVEY'S PROGRAM
IN
GEOTHERMAL ENERGY RESEARCH AND DEVELOPMENT

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The U.S. Geological Survey has had a specifically funded geothermal energy resource program since FY 1971. It evolved directly from 25 years of fundamental studies of hot springs and hydrothermal systems conducted by Survey scientists in an effort to better understand ore-forming processes and from many decades of geophysical, geochemical, and hydrological measurements applied to the study of both large and small regions. The basic objective of the current program is to develop an understanding of those principles which govern the nature, origin, and distribution of the geothermal energy resources of the United States, and the behavior of geothermal reservoirs during development and production.

The program draws heavily on the disciplines of geology, geochemistry, geophysics, and hydrology and consists of six broad elements: (1) development and testing of various components of a geothermal exploration technology; (2) identification of geothermal target regions in the U.S. and estimation of the nation's geothermal resources; (3) development of the science and technology for determining the energy potential of geothermal reservoirs; (4) development of techniques for assessing the energy potential of those parts of geothermal reservoirs currently at levels deeper than any thus far tapped; (5) investigations of rock-water geochemical interactions at elevated temperatures and pressures in order to develop the means of controlling reservoir permeability; and (6) investigations of geology-related environmental impacts associated with the fluid extraction. Approximately 25 percent of the program budget is designated for extramural research designed to supplement the in-house research effort and administered through a program of contracts and grants.

SESSION II

RESOURCES EXPLORATION AND ASSESSMENT

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SESSION II. RESOURCES EXPLORATION AND ASSESSMENT

SESSION CHAIRMAN: E. M. Shoemaker.

GEOPHYSICAL, GEOCHEMICAL, AND GEOLOGICAL INVESTIGATIONS OF THE DUNES GEOTHERMAL SYSTEM, IMPERIAL VALLEY, CALIFORNIA - W. A. Elders, J. Combs, T. B. Coplen, P. Kolesar, and D. K. Bird

THE COLORADO SCHOOL OF MINES NEVADA GEOTHERMAL STUDY - G. V. Keller, L. T. Grose, and R. A. Crewdson

HEAT FLOW AND GEOTHERMAL POTENTIAL OF THE EAST MESA KGRA, IMPERIAL VALLEY, CALIFORNIA - C. A. Swanberg

A BRIEF DESCRIPTION OF GEOLOGICAL AND GEOPHYSICAL EXPLORATION OF THE MARYSVILLE GEOTHERMAL AREA - D. D. Blackwell, C. A. Brott, T. T. Goforth, M. J. Holdaway, P. Morgan, D. Petefish, T. Rape, J. L. Steele, R. E. Spafford, and A. F. Waibel

ROLE OF THE U. S. GEOLOGICAL SURVEY IN ASSESSING THE NATION'S GEOTHERMAL ENERGY RESOURCES - G. P. Eaton (abstract only)

TERRESTRIAL HEAT FLOW STUDIES ASSOCIATED WITH THE RIO GRANDE RIFT AND NEIGHBORING GEOLOGICAL PROVINCES - M. Reiter, C. L. Edwards, C. Shearer, and C. Weidman (abstract only)

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GEOPHYSICAL, GEOCHEMICAL, AND GEOLOGICAL INVESTIGATIONS
OF THE DUNES GEOTHERMAL SYSTEM,
IMPERIAL VALLEY, CALIFORNIA*

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The Dunes anomaly is a water-dominated geothermal system in the alluvium of the Salton Trough, lacking any surface expression. It was discovered by shallow-temperature gradient measurements. A 612-meter-deep test well, drilled by the California Division of Water Resources, encountered several temperature-gradient reversals, with a maximum of 105°C at 114 meters.

Our program involves surface geophysics, including electrical, gravity, and seismic methods, down-hole geophysics and petrophysics of core samples, isotopic and chemical studies of water samples, and petrological and geochemical studies of the cores and cuttings. We aim (a) to determine the source and temperature history of the brines, (b) to understand the interaction between the brines and rocks, and hence (c) to determine the areal extent, nature, origin, and history of the geothermal system.

The source of the fluid is partially evaporated Colorado River water, which equilibrated with the rocks at temperatures ranging from 100 to 170°C. The existence of seven zones of dense, impermeable, grey quartzite in the upper 300 meters indicates that subsurface flow is largely horizontal, that rock-water interactions are essentially self-sealing, and that incursions of hot brine into the system are episodic.

These studies are designed to provide better definition of exploration targets for hidden geothermal anomalies and to contribute to improved techniques of exploration and resource assessment.

The presentation which follows is in three parts. Part A reviews some of the geochemical studies by Coplen and Kolesar; Part B by Elders and Bird is concerned with the geology of the silicified cap rocks. Part C by Combs, dealing with geophysical investigations, was not supplied.

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** Now at the University of Texas, at Dallas.

PART A: GEOCHEMISTRY

T. B. Coplen and P. Kolesar

A geothermal test corehole, DWR Dunes No. 1, was drilled in the Dunes geothermal anomaly by the State of California Department of Water Resources. Water samples from this geothermal system were collected from perforations at 109- and 260-meter depths. These water samples were analyzed for chemical and isotopic composition. A total dissolved solids of 4000 ppm was measured on samples from both depths, and this relatively low value may be a consequence of the low temperatures (100°C) measured in this well. Samples from both depths were nearly identical in chemical and in oxygen and hydrogen isotopic composition, suggesting that the water from the two perforated intervals is derived from the same source.

Oxygen and hydrogen isotope studies of water samples indicate that the source of the geothermal fluid is partially evaporated Colorado River water. The percentage of local rainfall in the geothermal fluid is below detection. The geothermal fluid is probably derived from a source deeper than 400 meters because aquifers shallower than this in this region usually have a significant local rainfall component.

An investigation of chloride/bromide ratios was used to determine the source of the salt in the geothermal fluid from Dunes. The ratio Cl/Br in DWR Dunes No. 1, in the Salton Sea geothermal system, and in Colorado River water is identical at 1600. This result may suggest that the salt in the Salton Sea geothermal system and in the Dunes geothermal anomaly is derived from the Colorado River and that this water has not done any leaching or been mixed with water from other sources.

Several chemical thermometers were applied to the water samples from DWR Dunes No. 1. The silica geothermometer, sodium-potassium-calcium geothermometer, and the calcite-water oxygen isotope geothermometer yielded temperatures of 138, 170, and 117°C, respectively, for DWR Dunes No. 1. These are all greater than the 100°C temperature measured during a pumping test and during geophysical temperature surveys. These results suggest that the geothermal reservoir may be considerably hotter than that measured by this technique.

Clearly, further geophysical studies, such as gravity, seismic refraction, electrical resistivity, and magnetotelluric sounding studies, are needed to locate the reservoir of geothermal fluid in the Dunes system, and these are now in progress. If a reservoir of sufficient size can be located, further drilling at the Dunes geothermal anomaly may be justified.

I. INTRODUCTION

The demand for new energy in the United States has been rising at an annual rate of 7 to 10 percent. If this rate continues, it will approximately double by 1983. The demand has been increasing faster than supply, and reserves are taxed during periods of heavy demand as illustrated by recent power brown-outs in large portions of the United States. This situation has become critical. However, the immediate development of new energy sources should help ensure adequate energy supplies for the future growth of our nation.

One of our resources which is virtually undeveloped and can help alleviate both water and energy shortages is geothermal resources. There are several incentives to develop this resource, for instance, low pollution levels compared to alternative energy sources and the relatively low capital installation costs.

As part of a continuing investigation of geothermal resources, the University of California, Riverside (UCR) is investigating several geothermal anomalies in the Imperial Valley of California. One of the anomalies, the Dunes anomaly (shown in Fig. A-1) was discovered by R. W. Rex, utilizing temperature gradient measurements. Further geophysical investigation of this anomaly indicated a correlation between a positive gravity anomaly and high geothermal gradients in shallow boreholes (Ref. A-1). A temperature of 112°C was observed at a depth of 114 meters in borehole USBR-UCR No. 115. These data and the recovery of silicified sandstone suggested the existence of an intensely silicified nearly impermeable cap which confined the underlying geothermal fluids. It was proposed that hot water from a geothermal environment at depth is precipitating dissolved silica in the upper zone of lower temperature, forming a self-sealing geothermal reservoir. These data and the consequent hypothesis suggested that the Dunes anomaly is a prime target for additional concentrated study. Thus, the California Department of Water Resources (DWR) in cooperation with UCR, drilled a 612-meter-deep test well at the Dunes anomaly, DWR Dunes No. 1. Figure A-2 shows the temperature gradient, electric log, core recovery, and casing perforation program.

In order to maximize the scientific yield of this program, UCR proposed to, and was funded by, the RANN Division of the National Science Foundation a geological, geochemical, and geophysical investigation of the Dunes hot water anomaly. Core studies include the measurement of density, sonic velocity, thermal conductivity, electrical resistivity, permeability, porosity, magnetic susceptibility, mineralogical composition, chemical composition, and isotopic composition. Optical microscope, electron microprobe, and scanning electron microscope studies have been conducted to study cementation, metamorphism, and the response of sedimentary minerals and ground waters to a geothermal

environment (Ref. A-2). Various geochemical thermometers are being applied to this system where in situ temperatures can be measured directly. Water sample investigations include various chemical and isotopic studies. Areal geophysical investigations, which include seismic refraction, electrical resistivity, and gravity, are being conducted to delineate the subsurface geometry of the silicified zone and to determine the extent of the geothermal system.

The aims of the proposed work included:

- (1) Improving our understanding of how to explore for and characterize potential geothermal systems in sedimentary environments by integrating a broad geochemical, geophysical, and geological study on a single hot water geothermal anomaly.
- (2) Establishing the existence of a shallow low-salinity hot water field that could be developed for power and water desalination.
- (3) Demonstrating that a circulating geothermal hot water system in alluvium can create its own seal and build up higher shallow temperatures than would otherwise be expected.
- (4) Establishing criteria for recognizing potential geothermal areas from rock and water geochemistry and from geophysical criteria.
- (5) Providing a potential test site for geothermal experimental studies of other investigators.

In order to communicate these results as soon as possible to those who are interested and can make use of them, the results are being issued as a series of technical papers in addition to being submitted to scholarly journals.

A preliminary report incorporating the initial results of the combined geophysical, geochemical, and geological results was issued shortly after the well was completed (Ref. A-3). This new report is one of a series giving more detailed results based on the work of the past two years. It deals with the chemical and isotopic studies of the geothermal fluids from DWR Dunes No. 1. Elders and Bird in Part II (Ref. A-2) have considered the petrological aspects of the Dunes anomaly. In subsequent reports the oxygen and carbon isotope abundances of core samples and site geophysics will be discussed.

II. CHEMICAL STUDIES

The chemistry of water samples from a geothermal system is of importance for a variety of reasons. The abundances of dissolved chemical constituents put constraints on how the system can be developed for power. The chemistry of geothermal fluids enables studies to be conducted on the origin of the salt in the geothermal system. The abundances of various species and the ratio of the abundances of various species can be used to estimate temperatures in geothermal systems and to explore for geothermal anomalies.

During September of 1972 the casing of DWR Dunes No. 1 was perforated in three zones, two where the temperature versus depth curve (Fig. A-1) indicated the highest temperatures, and the third near the bottom of the hole. The interval 572-585 meters was perforated September 14, 1972. The well flowed at about 4 liters per second. Samples for chemical and isotope analysis were taken both from the surface flow and by bailing. A bridge plug was installed and the interval 259-271 meters was perforated. This zone did not flow. The water level was about 9 meters below the surface. Samples were obtained by bailing. The interval 104-116 meters was perforated and samples were obtained by bailing because again the flow was not artesian. Depth to the water level was 9 meters. No bridge plug was installed between the upper two perforations so that additional perforating could be accomplished without need of a drill rig to drill out the bridge plug.

The chemical analysis of the samples from these three zones suggested that the reliability of these samples was in question due to contamination by drilling mud. Therefore, a second attempt at sampling water from DWR Dunes No. 1 was tried in May, 1974. Because a bridge plug had been installed at 556 meters, only the upper two aquifers could be sampled. An evacuated stainless steel cylinder with a glass breakoff was lowered to 109 meters. A metal sender was employed to actuate the filling of the cylinder. A second sample was obtained from 260 meters in an identical manner. A downhole lift pump was then installed at a depth of 42 meters, and the well was pumped for several hours until the leather gaskets on the downhole pump assembly failed. After replacement, several thousand liters were pumped from the formation at a rate of 10 liters per minute. Water temperatures up to 100°C were recorded. After approximately one day of pumping, two water samples were taken one hour apart. The pump was then shut down.

The two samples collected by evacuated cylinders and the two pumped samples were split into unfiltered, filtered, and filtered acidified aliquots. Aliquots for isotopic analysis were also taken. Chemical analyses were performed by the California Department of Water Resources and by UCR. A summary of the results are listed in Table A-1 in parts per million by weight. The stable isotope analyses are discussed in the next section.

The analyses of the two pumped samples and the two samples collected by evacuated cylinder are nearly identical. Column 2 in Table A-1 is an analysis of the last pumped sample and the third column is an analysis of the 260-meter-deep sample collected with the evacuated cylinder. The agreement among all four water samples suggests that these analyses are good. The observation that the samples collected opposite each perforation with the evacuated cylinder are identical in chemical and isotopic composition suggests that there certainly is a single source for the water entering both perforations unless mixing in the borehole is complete. If we discount mixing in the well, one explanation for this observation is vertical flow of geothermal fluid in formations penetrated by DWR Dunes No. 1.

The total dissolved solids in these samples is relatively low, about 4000 ppm, compared to other geothermal systems in the Imperial Valley (15,000 - 250,000 ppm). In the hot water geothermal systems in the Imperial

and Mexicali Valley, an increase in temperature is usually accompanied by an increase in salinity. Thus, the low salinity measured at Dunes may be a consequence of low temperatures in this system.

Silica, ammonia, and zinc were not measured on the sample obtained with the evacuated cylinder from the 259-271-meter perforation. The error in the chemical analyses is unknown. However, it is probably not great because the sum of the cations and anions in both analyses is within 5 percent of the measured TDS.

The abundances and the ratio of the abundances of several chemical constituents of geothermal brine have been shown to be useful indicators of subsurface temperature (Ref. A-4). In order to apply this geothermometer, one must make the following assumptions: (1) that chemical equilibrium exists in the geothermal system, (2) that transport of the geothermal fluid to the surface is sufficiently quick to prevent precipitation or retrograde exchange at lower temperatures, and (3) that there is negligible contamination by other sources of water. The simplest of the geochemical thermometers is the silica geothermometer. The quantity of silica in a solution in a sample of geothermal fluid increases as a function of temperature. The calibration curve is reported by Fournier and Truesdell (Ref. A-5). The silica content measured in various samples from DWR Dunes No. 1 corresponds to a temperature of $138 \pm 10^{\circ}\text{C}$. The measured temperature is 100°C .

Another geothermometer which has proved useful is the sodium-potassium-calcium geothermometer. The use of this geothermometer is discussed by Fournier and Truesdell (Ref. A-6). The equilibration temperature is a function of

$$\log \frac{\text{Na}}{\text{K}} + \beta \log \frac{\sqrt{\text{Ca}}}{\text{Na}}$$

where β is 1.333 unless equilibrated temperatures are above 100°C , in which case it is 0.333. The Na-K-Ca temperature of DWR Dunes No. 1 geothermal fluid is 170°C , a value much higher than actually measured (Fig. A-2). The explanation of this may be:

- (1) Chemical equilibration does not exist in the region of DWR Dunes No. 1.
- (2) The Na-K-Ca geothermometer cannot be applied at the Dunes geothermal anomaly because the mineralogy at Dunes is different than at the systems used to calibrate this geothermometer. This possibility appears to be the least likely.
- (3) The temperature at depth at the source of the geothermal fluid is greater than the 100°C temperatures measured during our water sampling or geophysical logging.

Explanation (3) appears to be most likely if one also considers the temperature of 138°C determined from the silica geothermometer.

The calcite-water oxygen isotope geothermometer has been applied to DWR Dunes No. 1. Coplen (Ref. A-7) reported temperatures of 97 and 117°C for two samples of calcite from the core, assuming oxygen isotope equilibrium between calcite and water.

These results suggest that a geothermal reservoir may exist at the Dunes anomaly with a temperature of 97, 117, 138, or 170°C. In order to examine this possibility of a hot geothermal reservoir at the Dunes anomaly, additional site geophysics is required. This is presently being undertaken by Shawn Biehler at UCR and Jim Combs now at the University of Texas, Dallas. If it is possible to identify a geothermal reservoir of sufficient magnitude, further drilling at the Dunes anomaly is probably justified.

The ratio of chloride to bromide in water has been used to investigate the origin of salt in geothermal systems (Refs. A-4 and A-8). Cl/Br ratios of the ocean and Cerro Prieto geothermal field in Baja California are 300 and 400, respectively. The ratio in the Salton Sea geothermal system and the Colorado River is 1600. This ratio in all of the samples from DWR Dunes No. 1 is 1600, identical to that of the Salton Sea system and the Colorado River. White (Ref. A-9) has suggested that the very saline brine in the Salton Sea geothermal system is derived from the solution of evaporites, which were formed from Colorado River water. Because the Cl/Br ratio of water from the Salton Sea geothermal field and from DWR Dunes No. 1 is identical with that from the Colorado River, it is possible that the source of the salts in both these geothermal anomalies is Colorado River water. However, the situation is probably not so simple as pointed out by Rex (Ref. A-8), because Cl/Br ratios in evaporites are usually highly variable and the Cl/Br ratio of salt from local precipitation is much lower than 1600. Future measurements on other geothermal systems in the Imperial Valley should shed light on the problem of the origin of the salts. Note that the origin of the salts and water in a geothermal system may be different. This possibility is discussed by Rex (Ref. A-8) for Cerro Prieto. For the Dunes geothermal system we demonstrate in the section on stable isotopes that the water in this system is most likely derived from partially evaporated Colorado River water.

III. STABLE ISOTOPE STUDIES

The primary stable isotopic species of water are H_2O^{16} , H_2O^{18} , and HDO. These stable isotopes can be employed for a variety of hydrological investigations (Ref. A-10). Water samples from DWR Dunes No. 1 were employed in a stable isotope investigation directed towards identification of the source of the water in the Dunes geothermal anomaly.

Hydrogen isotope abundances in this study were determined on a 5-cm radius, 180-degree sector, isotope ratio, mass spectrometer (Ref. A-11) from hydrogen quantitatively extracted from an aliquot of the water sample by reaction with hot uranium metal. Corrections have been made for H_3^+ contribution to the mass-3 ion beam and for mixing of the sample and standard

gases due to glass valve leakage (Ref. A-12). The hydrogen isotopic composition of water samples is reported in parts per thousand difference ($^{\circ}/\text{oo}$) from Standard Mean Ocean Water (SMOW) (Ref. A-13). Thus,

$$\delta D(^{\circ}/\text{oo}) = \left[\frac{\left(\frac{D}{H} \right)_{\text{Sample}}}{\left(\frac{D}{H} \right)_{\text{SMOW}}} - 1 \right] 1000$$

The precision of the hydrogen isotopic analyses is $\pm 1^{\circ}/\text{oo}$.

The oxygen isotopic composition of water samples was determined on a double-focusing double-collecting isotope ratio mass spectrometer (Ref. A-14) by analyzing an aliquot of carbon dioxide which had been isotopically equilibrated with the water sample in a 25.0°C temperature bath (Ref. A-15). Corrections were made after Mook (Ref. A-12). The oxygen isotopic composition of water samples is reported relative to SMOW in the per mil notation:

$$\delta O^{18}(^{\circ}/\text{oo}) = \left[\frac{\left(\frac{O^{18}}{O^{16}} \right)_{\text{Sample}}}{\left(\frac{O^{18}}{O^{16}} \right)_{\text{SMOW}}} - 1 \right] 1000$$

The precision of the oxygen isotope analyses is $\pm 0.1^{\circ}/\text{oo}$.

As discussed by Craig (Ref. A-16) and Coplen (Ref. A-17), the stable isotope technique is useful in determining the origin of water in geothermal systems because:

- (1) The oxygen and hydrogen isotopic compositions of precipitation differ in general from one locality to another due primarily to differences in the temperature of precipitation. Craig (Ref. A-18) found a linear correlation between δD and δO^{18} for meteoric water samples from all over the earth such that

$$\delta D = 8\delta O^{18} + 10$$

Samples from colder locations are more negative in δD and δO^{18} while precipitation from equatorial zones is closer to SMOW.

- (2) A geothermal system has negligible effect upon the hydrogen isotopic composition of the water flowing through the system because the quantity of hydrogen in rocks is so low. The hydrogen isotopic composition of precipitation which enters a ground water

system and flows through that system is in general unchanged. Thus, hydrogen isotopic composition can serve to "tag" water from different sources.

- (3) The oxygen isotopic composition of precipitation samples which enters a geothermal system can be modified if the system is sufficiently hot (150°C or greater) due to exchange of oxygen in water with oxygen in the rock. The net effect is to increase the O^{18} content of the water and decrease the O^{18} abundance in the rock. This " O^{18} -shift" is discussed by Craig (Ref. A-16).

Figure A-3 is a plot of δD versus δO^{18} for water samples from DWR Dunes No. 1, the Mesa geothermal system, central Imperial Valley wells, and other Imperial Valley wells. Figure A-3 demonstrates that most of the water samples from the Imperial Valley plot along a line which is the path followed by evaporating water from the lower Colorado River (Lake Mead). Note that the isotopic composition of local precipitation lies far to the left of this evaporation path. This strongly suggests that most of the subsurface water in the Imperial Valley was derived from the Colorado River. Only near the margins and in a few shallow aquifers is there significant water derived from local precipitation as shown by the open well in Fig. A-3.

The geothermal fluid from both (upper) perforations of DWR Dunes No. 1 plot in Fig. A-3 with central Imperial Valley wells, suggesting that the source of the water in the Dunes system is not local precipitation, but is deeper partially evaporated Colorado River water. The samples from both the 110- and 260-meter aquifers are identical in isotopic composition (see Table A-1) and plot at the same point on Fig. A-3. This suggests that both are derived from the same source.

The samples from DWR Dunes No. 1 do not show the oxygen isotope shift shown by the sample of geothermal brine from Cerro Prieto (Fig. A-3). This may be due to the fact that

- (1) The higher temperatures at Cerro Prieto promote oxygen exchange between water and silicates, but temperatures at the Dunes are not sufficiently high to promote exchange of oxygen between water and silicates.
- (2) So much water has passed through the Dunes system that the oxygen isotopic composition of the rock has been lowered such that it is in equilibrium with water entering the system. Thus, there would be no chemical potential to increase the O^{18} content of water entering the system.

In order to investigate which of these hypotheses may be correct, we are in the process of analyzing the carbonates and silicates from this well for oxygen and carbon isotopic composition. The results of this study will be issued shortly as a technical report in this series.

The Mesa geothermal system, whose location is shown in Fig. A-1, is being developed by the U.S.D.I. Bureau of Reclamation to provide desalted

water to augment the flow of the Colorado River. Because the anomaly is geographically near the Dunes anomaly and because the geology of the system is very similar to that of the Dunes anomaly, it is informative to examine the isotopic composition of water samples obtained from the Mesa anomaly. Figure 3 shows 6 samples from the Mesa system. Samples 1 and 2 are from two shallow aquifers about 50 and 80 meters deep. They are distinctly different in both oxygen and hydrogen isotopic composition than deeper sample numbers 3, 4, and 5. This suggests that near surface ground water was not derived from the geothermal brine at depth. The isotopic composition of these shallow samples suggests that a large proportion of the near-surface water was derived from local precipitation. Samples 3, 4, and 5 were obtained during drill stem tests of Mesa 6-1 from depths of 780, 1350, and 1650 meters, respectively. They plot near the Colorado River water evaporation line in Fig. A-3. In addition, two of these samples plot near the central Imperial Valley well waters. These results strongly suggest that the water in the Mesa geothermal system was, like that of the Dunes anomaly, derived from Colorado River water (Lake Mead). Sample 6 is a brine from which steam was flashed. It lies to the right of the evaporation line, demonstrating that steam depleted in O^{18} flashed from this brine, thus enriching the brine in O^{18} . This result shows the importance of obtaining a quantitative sample of the fluid in order to ensure accurate stable isotope analyses.

In conclusion, the oxygen and hydrogen stable isotope studies of water samples from DWR Dunes No. 1 indicate that the water samples from the perforations at 109 and 260 meters are identical in oxygen and hydrogen isotopic composition within experimental error. These results strongly support the conclusion that geothermal fluid obtained from both of these aquifers flows from the same source. The source of the geothermal fluids from DWR Dunes No. 1 is moderately deep ground water (probably greater than 400 meters), containing a negligible amount of local precipitation. The geothermal brine was derived from partially evaporated Colorado River water.

IV. OTHER GEOCHEMICAL STUDIES BY UCR

C^{14} R. E. Taylor at the University of California, Riverside is measuring the C^{14} abundance of dissolved carbonate species in order to obtain information on the "age" of the water in the Dunes geothermal system. The age of the water in geothermal systems is of particular importance in estimating the lifetime of a geothermal system developed for its energy potential. Should this technique be successively refined here, it can be used on other hot water geothermal systems. C^{14} studies have not proved fruitful at the Salton Sea geothermal system because very large quantities of "dead" CO_2 are released from decarbonation reactions of ancient carbonates, which occur in the range of $300^{\circ}C$. Thus, the ages obtained are infinite. We are hopeful that the C^{14} technique may be of use in the Dunes geothermal system because the temperatures are much less than those at the Salton Sea geothermal field.

V. GEOCHEMICAL STUDIES BY OTHER ORGANIZATIONS

Work is presently being carried out by the geothermal resources group at Stanford University under the direction of Professor Paul Kruger to investigate environmental aspects and reservoir properties of the Dunes anomaly utilizing radon abundances.

ACKNOWLEDGMENTS

We wish to thank Dr. Jim O'Neil for hydrogen isotope analyses of DWR Dunes No. 1 geothermal waters. We acknowledge support from the State of California Department of Water Resources, in particular, Chuck White, John Ferguson, and George Burckhalter, for some of the chemical analyses and for help in sampling DWR Dunes No. 1 for geothermal fluid.

This research was supported by National Science Foundation Grant GI-36250 to W. A. Elders, T. Coplen, and J. Combs.

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Table A-1. Chemical and isotopic composition of water samples from DWR Dunes No. 1

Chemical/isotope	From 104-116-meter perforation, ppm	From 259-271-meter perforation, ppm
Lithium	1.85	1.85
Sodium	1262	980
Potassium	103	107
Magnesium	1.7	1.4
Calcium	136	101
Strontium	0.6	0.5
Manganese	0.07	0.07
Iron	0.36	0.03
Copper	0.00	0.09
Zinc	1.14	
Cadmium	0.10	0.05
Arsenic	0.06	0.02
Lead	0.00	0.00
Fluoride	4.6	1.9
Chloride	2021	2040
Bromide	1.26	1.28
Iodide	0.094	0.13
Sulfate	178	140
Nitrate	0.0	0.0
Bicarbonate ^a	76	67
Carbonate ^a	0.04	0.03
Ammonia	0.84	
pH ^a	6.58	6.43
Boron	2.2	1.9
Silica	118	
TDS	3940	3950
δD	-94 ‰	-94 ‰
δO ¹⁸	-10.77 ‰	-10.80 ‰
δC ¹³ of bicarbonate	- 8.6 ‰	

^aField analysis; all other analyses are laboratory analyses.

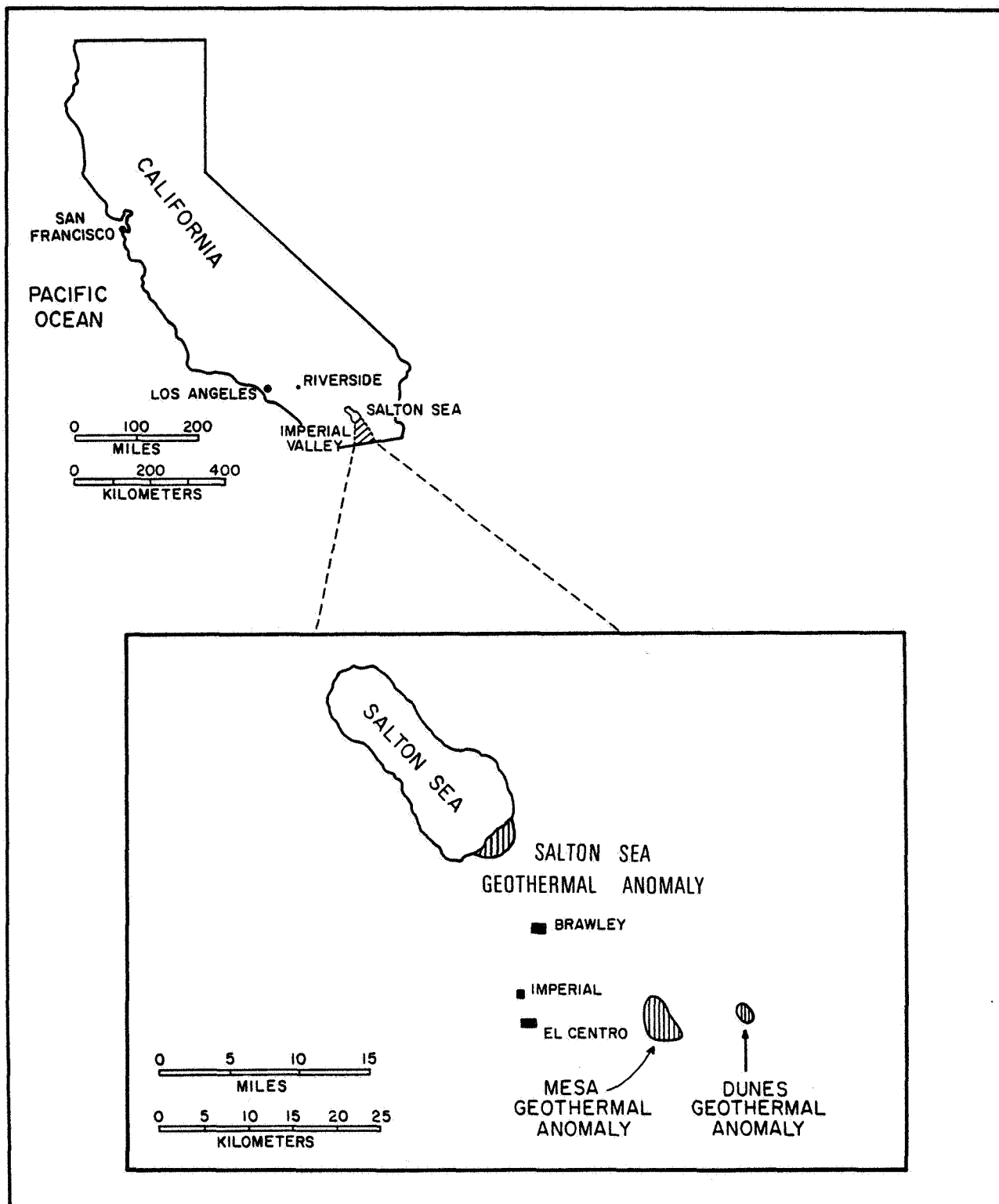


Fig. A-1. Imperial Valley geothermal anomalies

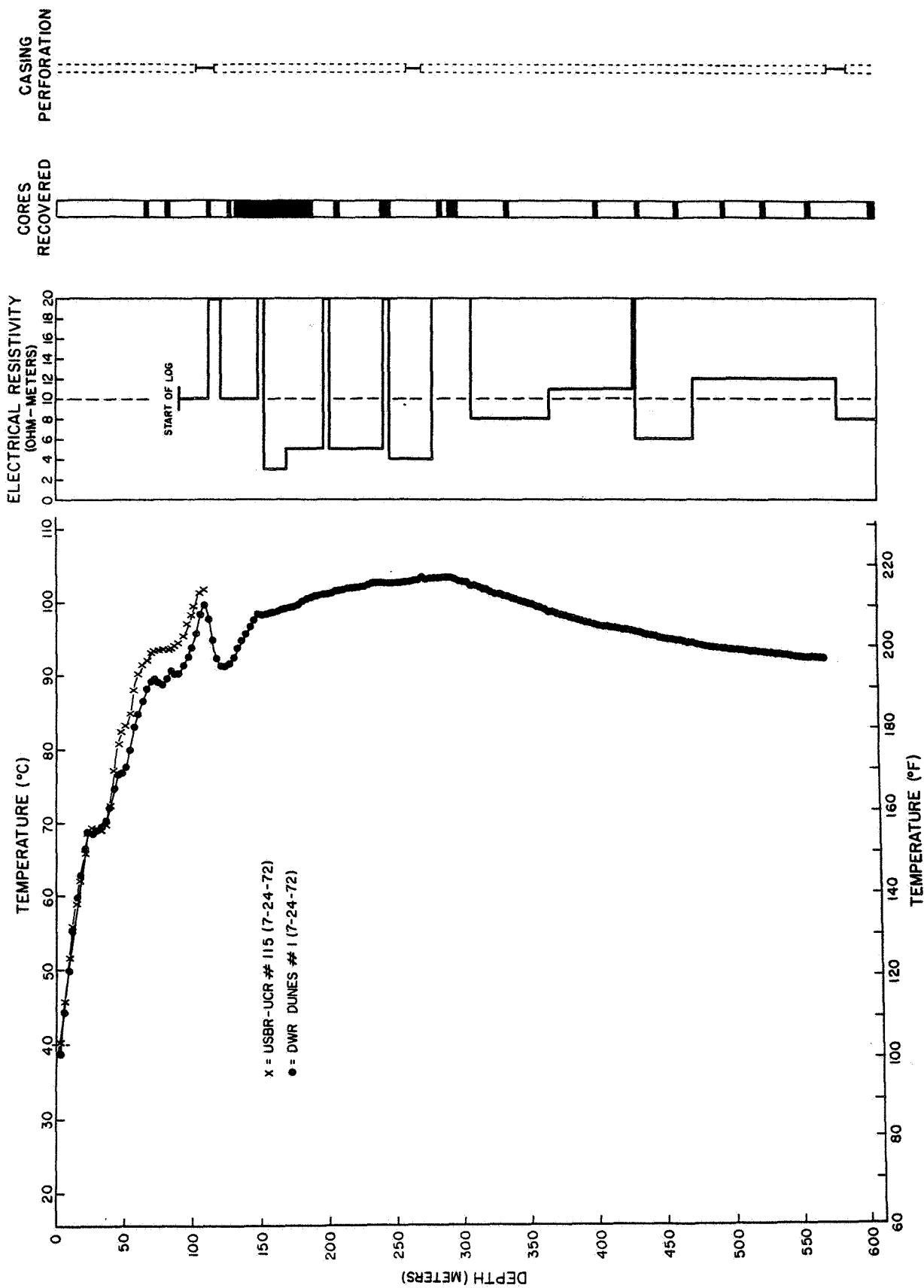


Fig. A-2. Temperature gradient, electric log, core recovery, and casing perforation program

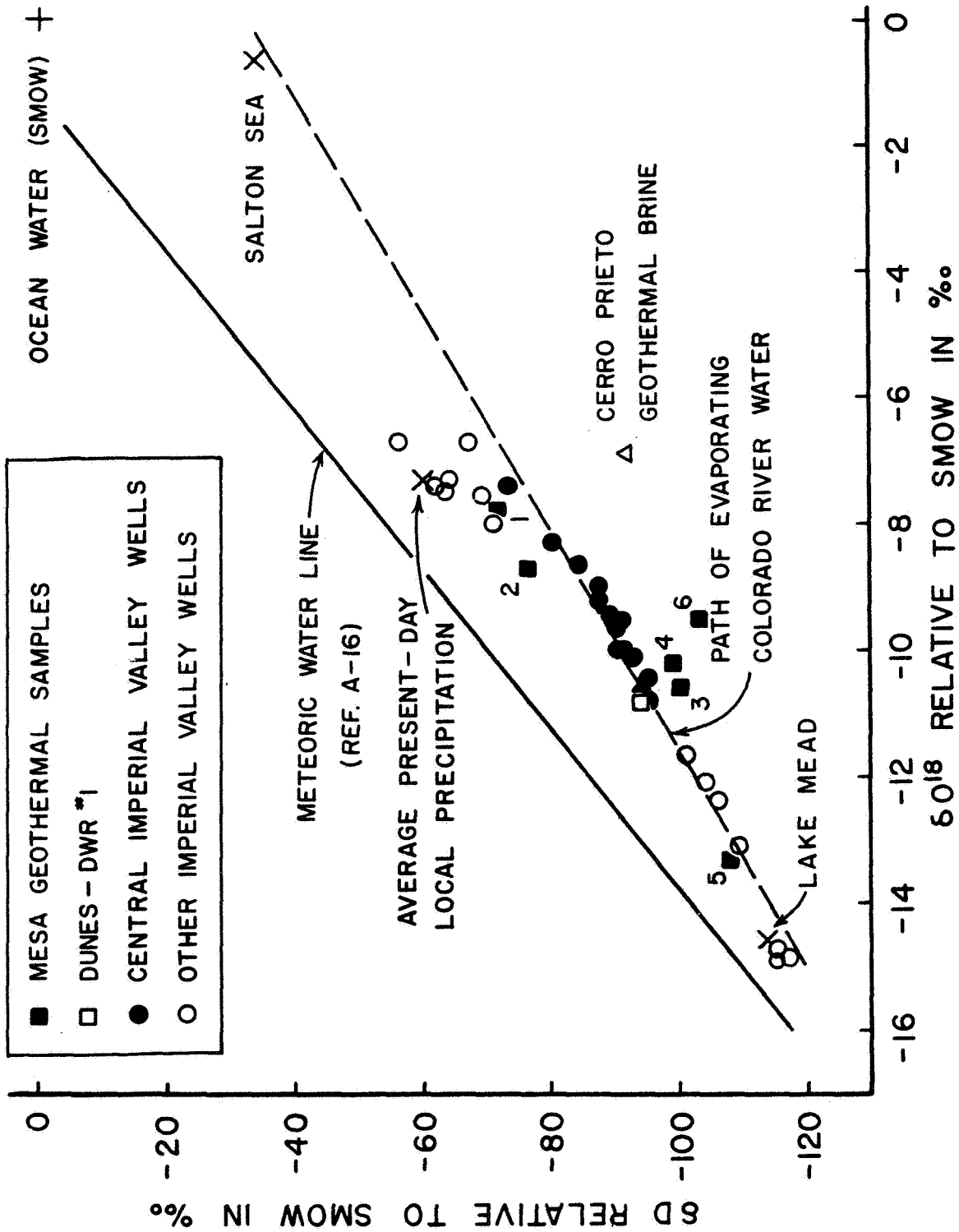


Fig. A-3. δD versus δO^{18} for water samples from DWR Dunes No. 1

PART B: GEOLOGY

W. A. Elders and D. K. Bird

Extensive alteration of sedimentary rocks by geothermal brines is common in a zone of high heat flow within the Salton Trough, the landward extension of the Gulf of California rift system. Several localized areas of very high temperature gradients at shallow depth, accompanied by positive gravity anomalies, occur within this zone.

A 612-meter deep test well encountered a maximum of 104°C at the 285-meter depth in the Dunes anomaly, at the southeast margin of the Trough. The rocks penetrated were deltaic sediments deposited by the Colorado River. Water samples recovered are alkaline sodium chloride brines with up to 3000 ppm of total dissolved solids. In the upper 300 meters of the hole, there are seven zones of dense gray quartzite formed by the reaction of the brines with the permeable sandstones. Precipitation of quartz, adularia, and pyrite has made the sediments impermeable and increased their density from 2.2 to 2.6 g-cm⁻³. The amount of silica precipitated is greatest below impermeable shale beds. However, extensive hydrothermal alteration is absent in the lower 300 meters of the hole, where only diagenetic processes seem to have occurred. This shows that the hydrothermal brines migrated laterally between impermeable barriers rather than vertically through the formations. Based upon studies of the textures it is evident that there have been various stages of hydrothermal and diagenetic alteration in each of these silicified zones. The presence of temperature gradient reversals and the existence of both diagenetic and hydrothermal alteration in fractures in silicified rocks suggests that the silicification was episodic. Brines of different oxidation state and presumably different temperatures have entered the system at various times.

It appears that when moderately hot brines encountered colder rocks, precipitation of quartz and feldspar made the rocks impermeable. Any further flow of water through the heavily silicified rocks was through later fractures.

Thus, water-dominated geothermal systems which operate in porous sandstones are essentially self-sealing. Convective overturn of the geothermal brine is very strongly influenced by the original and subsequent permeability of the system. A sealed

geothermal system, like this one, may therefore have no surface expression. However, the silica cap rock is a good exploration target for geophysical surveys and can give rise to high temperature gradients near the surface.

I. INTRODUCTION

An unusually clear-cut example of silicification of sedimentary rocks, by hydrothermal reactions at shallow depth, was discovered in test wells drilled into a geothermal anomaly in the southeastern part of the Imperial Valley of California, U.S.A. The Imperial Valley forms the northern end of a physiographic province known as the Salton Trough, which is a structural extension of the Gulf of California into the continent of North America (Fig. B-1a). The Salton Trough is a complex rift valley, partly filled to a depth of 6-7 km with sediments of late Tertiary and Quaternary age (Ref. B-1).

Several geothermal anomalies occur in the Imperial Valley north of the international border (Fig. B-1b). The best known of them is the Salton Sea geothermal field at the south end of the lake known by that name (Ref. B-2).

The only geothermal anomaly in the region that is currently being exploited occurs at Cerro Prieto, 20 km south of Mexicali, Mexico, where a 75-MW generating plant produces electricity from steam flashed from a water-dominated system (Ref. B-3).

The Dunes geothermal anomaly lies 15 km north of the international border on the east side of the Imperial Valley (Fig. B-1b). The anomaly, which is about 2.5 km² in extent, was discovered during geophysical surveys (Ref. B-4).

At this location a shallow temperature gradient anomaly occurs together with a 2-milligal positive, residual gravity anomaly (Ref. B-5) and a shallow, electrical resistivity anomaly of 2 ohm-m (Ref. B-6). The alignment of these anomalies parallel to the structural trend of the San Andreas Fault suggests that they are at least partly fault-controlled (Fig. B-1b).

A 612-m-deep test-well (Dunes DWR No. 1) was drilled into the anomaly by the California Department of Water Resources (Ref. B-7). The thermal gradient is complex with a maximum of 100°C at 110 m followed by a temperature inversion and another maximum of 104°C at 285 m (Fig. B-2).

A dense cap rock is developed in which seven distinct zones of intensive silicification of sandstones were observed. The highest temperatures recorded are all within shales and intensively silicified sands of low permeability. The well casing was perforated at three intervals: 572-585 m, 259-271 m, and 104-116m. The lower perforation in the well flowed at about 4 liters/second; the upper two perforations did not flow and water samples were obtained by bailing immediately after completing the well and by pumping a year and a half later. The waters recovered are primarily sodium chloride brines with about 3000 ppm of total dissolved solids (Table B-1).

Approximately 96 m of core were recovered, along with drill cuttings sampled every 3 m. This paper is primarily based upon petrological investigations of the cores and cuttings recovered together with interpretation of the subsurface geophysical logs. The emphasis is primarily placed upon the post-depositional changes in the sandstones.

II. STRATIGRAPHY AND SEDIMENTATION

The sedimentary rocks recovered are all terrigenous detritus of the Colorado River Delta, rich in quartz and feldspar. We have recognized four sedimentary facies: (a) deltaic sands; (b) interbedded sands, silts, and shales; (c) dune-graded sand sequence; and (d) channel fill conglomerates. The deltaic sand facies, which represents about 80% of the section, consists of medium to fine arenaceous sands and silty sands. The interbedded sands, silts, and shales, which locally contain calcite concretions and gypsum, are believed to be a lake deposit. The dune-graded sand sequence contains cyclical graded sand sequences which appear to be a braided stream delta deposit. It is interbedded with well-sorted sands believed to be reworked dune sands. The lower 300 m of the well records fairly continuous deltaic deposition with intercalated lake deposits. The upper 300 m records the history of active distributaries of the river, with channel fill conglomerates and deltaic sands.

III. POST-DEPOSITIONAL ALTERATION

We have distinguished between two different degrees of post-depositional alteration in these rocks: hydrothermal and diagenetic. Hydrothermal alteration, which is found only in the upper 300 m of the well, in the silicified zones, is of a much more intense kind than the diagenetic alteration, which is found above and below the silicified zones. The effects of both types of alteration are to reduce permeability and porosity and increase the density by cementation of sands to sandstones. For example, in the diagenetically altered sandstones, the porosity averages 30-35% and the bulk density 2.1 g-cm^{-3} , whereas the hydrothermally altered sandstones have porosities as low as 3-4% and average bulk densities of 2.6 g-cm^{-3} (R. Goss, unpublished data, 1974).

Two further groupings of the post-depositional alteration can conveniently be made. We can distinguish between interstitial mineralization and fracture mineralization on the basis of whether water-rock interaction occurred within the primary and secondary pores of the rock, or within natural fractures within the silicified zones.

A. Interstitial Mineralization

Below 300 m diagenesis has produced grayish sandstones with localized calcite cement and concretions. Other diagenetic effects are incipient overgrowths of quartz and chalcedony on detrital quartz sand grains and of adularia on detrital microcline, together with minor amounts of gypsum. In

spite of this cementation, the sandstones are poorly indurated and friable. Similar diagenetic effects occur in the upper 75 m of the well; however, these rocks are variable in color, from pink to brick red, due to varying amounts of disseminated hematite (Fig. B-3a).

Between 75 and 300 m, seven zones of hydrothermal alteration occur in which intensive interstitial mineralization of arenaceous sands has formed well-indurated gray quartzites. In the initial stages of this hydrothermal alteration, hematite is reduced to pyrite and syntaxial growth of quartz is common. In more intensive stages epitaxial pyramidal quartz overgrowths develop on lithic clasts and adularia overgrowths on altered plagioclase and orthoclase detrital grains. Optically continuous overgrowths are common, and the void space is almost entirely filled with quartz or chert (Fig. B-3b and c). This interstitial precipitation restricts the permeability, sealing off further penetration by brine.

The distribution of interstitial authigenic mineral facies is strongly stratified. At least four distinct zones or facies of mineralization with depth can be noted, each associated with accessory authigenic minerals. These are (a) hematite + calcite (0-75 m), (b) hematite + quartz + adularia (75-100 m), (c) quartz + adularia + pyrite (100-160 m and 200-300 m), and (d) calcite \pm gypsum \pm chloritized biotite facies (300-610 m). The zonation of these mineral assemblages with depth is illustrated in Fig. B-2 under the heading of interstitial mineralization.

The development of these zones is clearly stratigraphically controlled as the flow of the brine seems to have been initially controlled by impermeable shalt or silt beds which overlie six of the seven silicified zones (Fig. B-2). Presumably, the hot, silica-saturated brines moved laterally through the formation, controlled by impermeable beds, and, as they cooled, precipitated silica. This made the rocks even less permeable so that the process was essentially self-sealing.

B. Fracture Mineralization

Within the intensely silicified zones, any further flow of brine could only occur where later fractures developed. These are especially numerous in four of the highly silicified zones (Fig. B-2). Six zones or facies of fracture mineralization can be recognized in which the following minerals are dominant: (a) quartz, (b) adularia (Fig. B-3d), (c) pyrite (Fig. B-3e), (d) pyrite oxidized to hematite (Fig. B-3f), (e) and calcite. The zonation of these minerals with depth is also shown in Fig. B-2. Most of these changes can be described as prograde metamorphism in response to higher than normal geothermal gradient. However, the texture of hematite in the hematite facies shows that it formed as pseudomorphs after authigenic pyrite, both in the fractures and also disseminated through the host rock adjacent to the mineralized fractures.

All of the post-depositional alteration in this well seems to record rock-water reaction in a near-surface geochemical environment, in which there was strong stratigraphic control over lateral flow of brine through the system and in which there developed episodic prograde and retrograde reactions

in younger fractures. Thus, the depth interval containing the seven silica cap rocks appears to be part of a laterally extensive hydrothermal aquifer. The idea that lateral transfer and episodic incursions of different brines occurred is also supported by the presence of the temperature gradient reversals (Fig. B-2). It is noteworthy that the highest temperatures are measured in what are now the least permeable rocks, suggesting that brines colder than those formerly present have now entered the system. As indicated in Fig. B-2 between 70 and 300 m, there appears to be a hydrothermal aquifer in which flow is horizontal. One explanation offered for the retrograde development of hematite after pyrite is that this aquifer is encroached upon, above, and below by more oxidizing meteoric waters (Fig. B-2).

IV. SELF-SEALING

Figure B-4 is a very schematic "cartoon" for the flow of water envisaged. The core hole, DWR Dunes No. 1, is shown at the top left; the rest is largely conjectural. At some as yet unexplored depth, a heat source or geothermal reservoir heats meteoric water, permitting solution of silica, together with lesser amounts of K_2O , and Na_2O . Impermeable shale beds restrict flow of the brines in the system so that upward flow is along fractures. The hot water encounters impermeable clay barriers and moves laterally, cooling and precipitating quartz, chalcedony, adularia or pyrite, thus forming a self-sealing cap rock which further restricts the upward flow. The system is shown recharging by cold, dilute, meteoric water descending another system of fractures, precipitating carbonate and sulfate as it heats up.

Although convection is initially controlled by the original stratigraphy, the system is progressively modified through time until self-sealing becomes a dominant factor. The importance of cap rocks and self-sealing in certain geothermal fields has already been pointed out (Ref. B-8).

In the Dunes anomaly discussed here, the self-sealing has sealed off the geothermal fluids so that there is no surface expression of geothermal activity. The low thermal conductivity of these impermeable rocks permits a high temperature gradient near the surface. However, such cap rocks are an excellent target for geophysical exploration in searching for new geothermal areas. In particular, the Dunes geothermal anomaly is a readily accessible natural laboratory for studying the self-sealing mechanism and rock-water interaction in a geothermal area near the surface.

ACKNOWLEDGMENT

This research was supported by the RANN Division of the National Science Foundation of the United States of America.

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Table B-1. Partial chemical analyses of water pumped from
104-116-m level in the Dunes DWR No. 1 borehole
(Analyst P. Kolesar)

Sample	Field pH	Na, ppm	K, ppm	Ca, ppm	Si, ppm
1	6.65 at 79° C	1310	100	103	55
2	6.65 at 79° C	1330	100	104	55
3	6.58 at 87° C	1330	100	104	56
4	6.58 at 87° C	1340	100	103	55

Note: These partial analyses are preliminary values determined on water collected by pumping in June 1974. Earlier analyses of water collected by bailing are believed to be contaminated by drilling water (Ref. B-7). Analyses of total dissolved solids determined on earlier samples ranged from 1260-3040 ppm, whereas the new samples contain 3940 ppm.

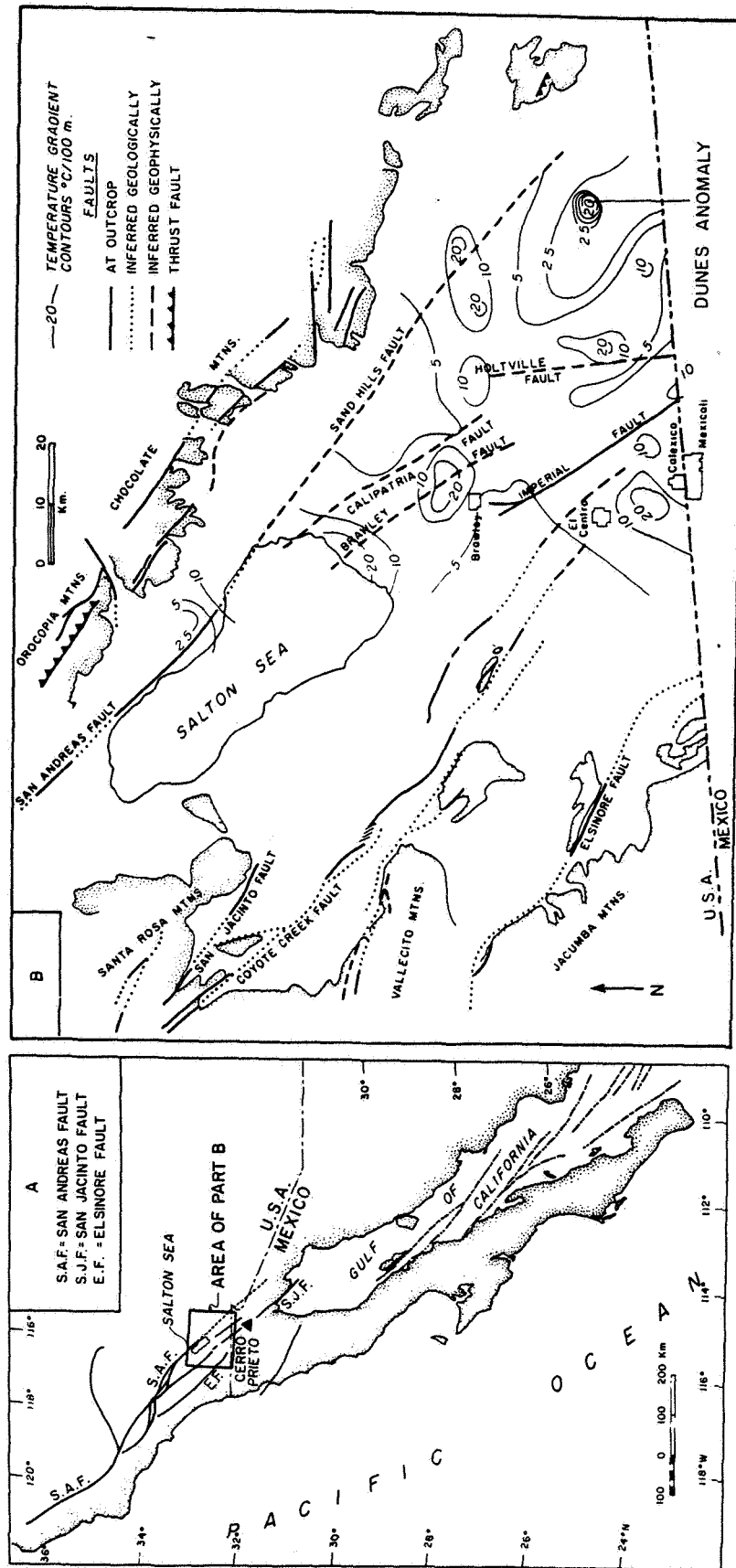


Fig. B-1. (a) Location of the Salton Trough; (b) faults and isotherms in the Imperial Valley showing the location of the Dunes geothermal anomaly

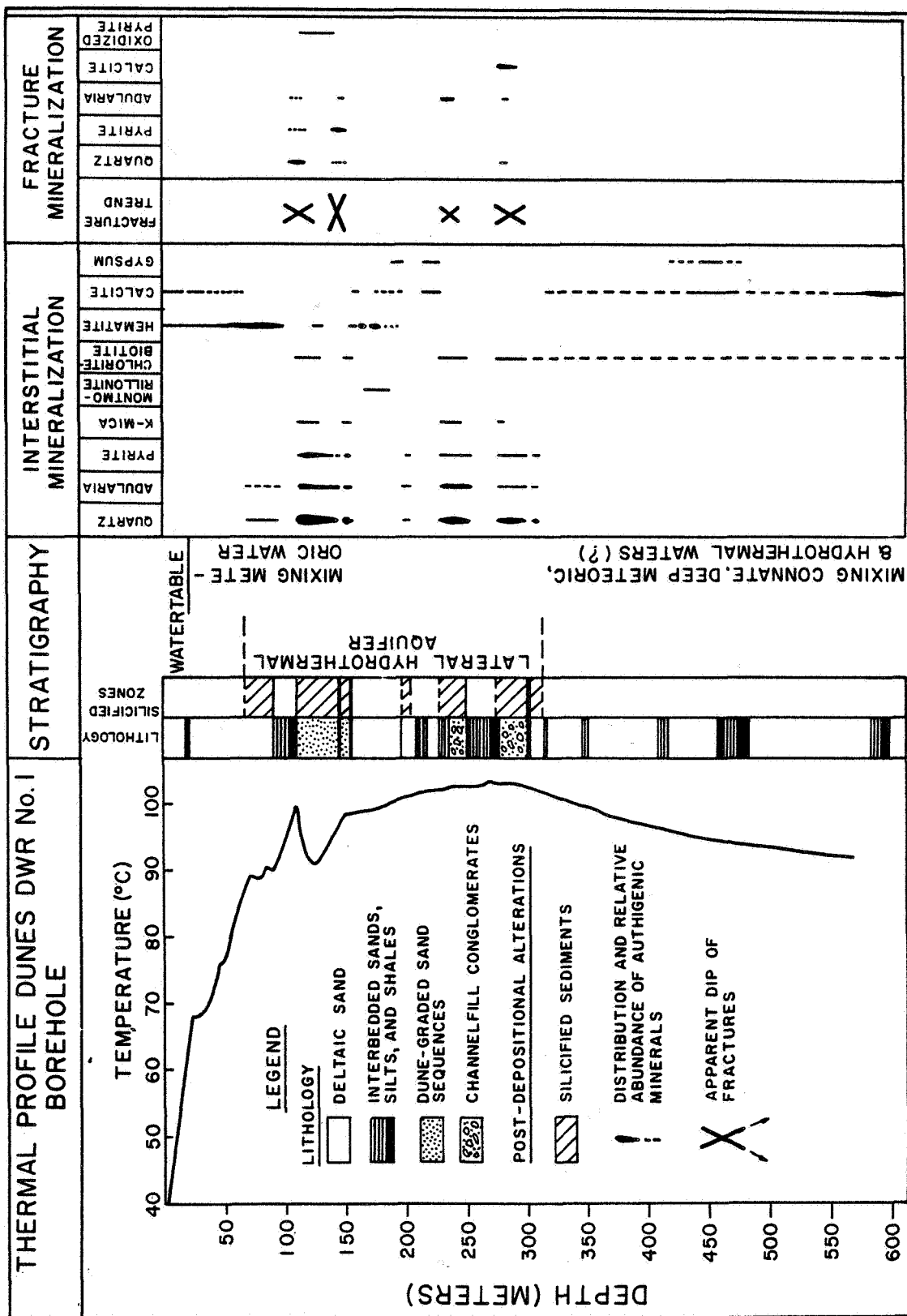


Fig. B-2. Summary of the thermal profile, physical stratigraphy, and post-depositional mineralization in pore spaces and fractures in the borehole of DWR Dunes No. 1

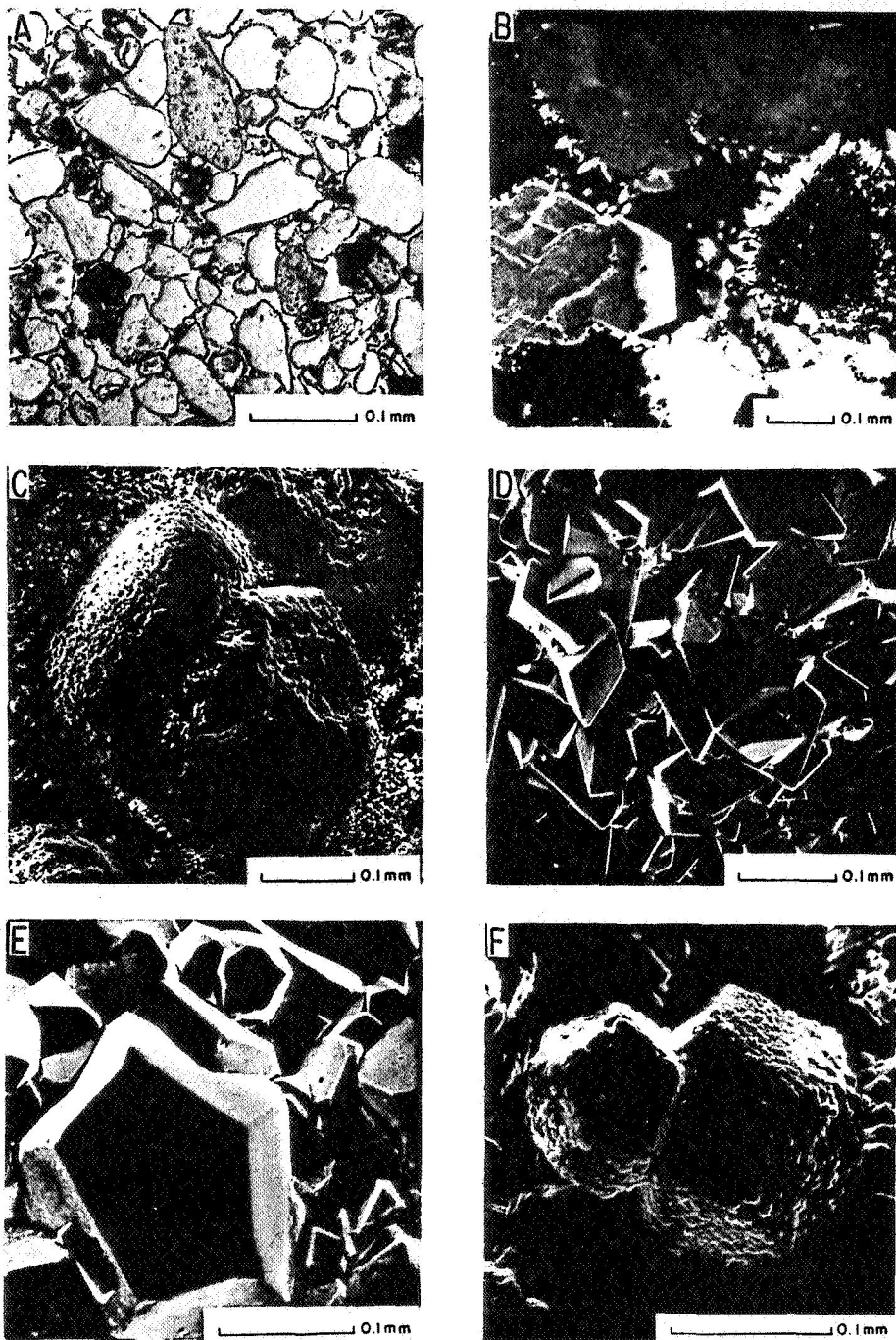


Fig. B-3. (a) Thin section of the core at 69.5-m depth in ordinary light--pale red arkosic sandstone with incipient quartz and hematite cement; (b) thin section of the core at 115.1-m depth with crossed polars--dense gray quartzite with overgrowths of quartz and adularia filling pore space; (c) core at 115.1 m showing quartz and feldspar overgrowths; (d) adularia coating a fracture surface at 246.6 m; (e) pyrite coating a fracture surface at 148.7 m; (f) hematite pyrite at 133.5-m depth

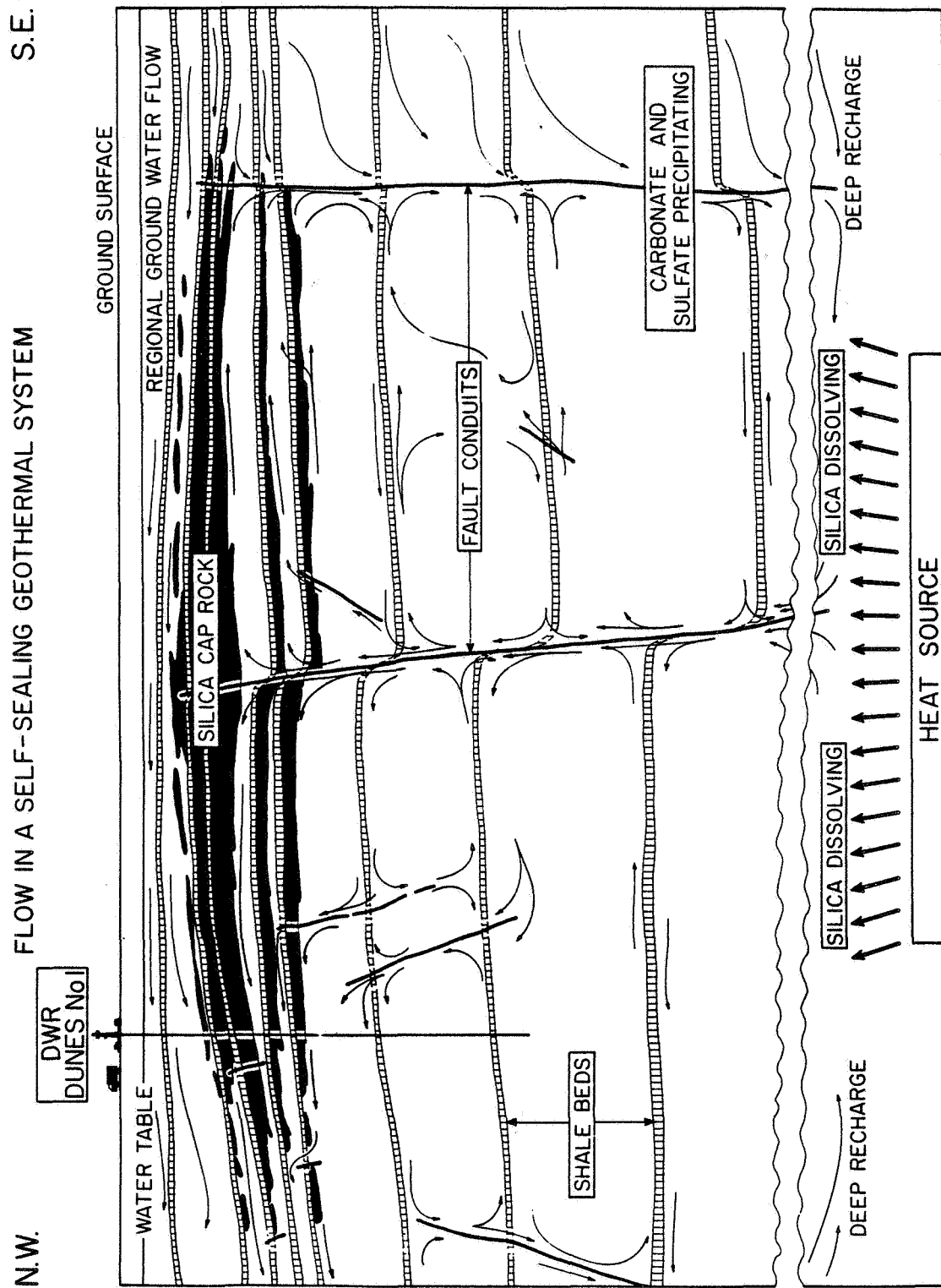


Fig. B-4. Schematic representation of the self-sealing mechanism

PART C: GEOPHYSICS

J. Combs

(Paper not supplied)

THE COLORADO SCHOOL OF MINES
NEVADA GEOTHERMAL STUDY

George V. Keller, L. Trowbridge Grose, and Robert A. Crewdson
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Geothermal systems in the Basin and Range Province of the western United States probably differ in many respects from geothermal systems already discovered in other parts of the world because of the unique tectonic setting. To investigate this, a study of the geothermal occurrences at Fly Ranch, approximately 100 miles north of Reno, Nevada, has been undertaken. Ample evidence for a geothermal system exists in this area, including the surface expression of heat flow in the form of hot springs, an extensive area of low electrical resistivity, and a high level of seismicity along faults bounding the thermal area. However, geophysical and geological studies have not yet provided evidence for a local heat source at depth. Additional detailed geophysical and geological studies, as well as drilling, must be completed before the geothermal system can be described fully.

I. INTRODUCTION

Large estimates of the potential capacity for producing geothermal power in the conterminous United States are based on the assumption that the Basin and Range Province has many unrecognized geothermal systems. These systems must differ in many respects from geothermal systems already discovered in other parts of the world because of the rather unique tectonic setting of the Basin and Range Province. In other areas, geothermal systems are usually closely associated with modern, easily recognized stages of volcanism, and the geothermal reservoirs are formed directly in the porous, pyroclastic rocks around these centers of volcanism. In the Basin and Range Province, the amount of modern volcanism is minor, raising a question as to whether or not enough heat is being supplied for the development of good geothermal systems. Also, if geothermal reservoirs are present, they may exist in porous alluvial sedimentary rocks or in fractured crystalline rocks rather than pyroclastics. At present, we cannot describe a Basin and Range Province geothermal system physically, so that geological and geophysical exploration programs can be designed specifically to find them.

The Colorado School of Mines has received support from the National Science Foundation under Grant GI 43866 to do a definitive geological and geophysical study of a Basin and Range type geothermal system.

The study is to be carried out on a geothermal prospect which might be considered to be typical of geothermal systems expected to be present in the Basin and Range Province. Fortunately, Sun Oil Company agreed to share with us the results of an exploration program that they have carried out for geothermal energy in the Basin and Range Province for the past decade. On the basis of their regional exploration results, we selected the Black Rock Desert, and more specifically, the Fly Ranch - Gerlach hot springs complex, as a prospect with a high probability of developing into an economically viable geothermal reservoir. The area lies approximately 100 miles north of Reno, Nevada, as shown in Figure 1. Many thermal springs lie within the prospect area, as indicated on Figure 1.

The plan for the study is to make use of the best available geological and geophysical techniques for evaluating the temperature, volume, and other pertinent characteristics of any geothermal reservoir within the survey area. The effectiveness of the exploration is to be evaluated by drilling a test hole to verify the predictions made on the basis of exploration results.

II. GENERAL GEOLOGY

The study is to be centered about the Fly Ranch hot spring complex, which lies in and around Hualapai Flat, about fifteen miles north of Gerlach, Nevada. A geologic map of the area is shown in Figure 2. Hualapai Flat is a topographic (and probably structural) embayment of recent sediments into the Granite Range. It is separated by a low saddle from the extensive Black Rock Desert to the east. It is bounded on the south and west by a granite massif (the Granite Range), and by thick volcanic piles on the northwest, which are in part continuous to the west with the volcanic rocks of the Modoc Plateau.

The sequence of events recorded by the rocks of the area are:

- (1) Deposition and subsequent thermal metamorphism of late Paleozoic (?) volcanic and sedimentary rocks.
- (2) Intrusion of Cretaceous granodiorite into the late Paleozoic (?) volcanic and sedimentary rocks, with profound erosion of the land surface.
- (3) Extrusion and intrusion of Tertiary volcanic rocks.
- (4) Quaternary lake cycles.
- (5) Recent faulting.

The late Paleozoic rocks are, as a group, the oldest rocks exposed in northwestern Nevada. They have not been studied and can only be described as a sequence of metamorphosed flows, tuffs, breccias, and sedimentary rocks. They crop out as several small hills roughly circling Hualapai Flat.

The Granite Range massif is, on the basis of normative and modal quartz-orthoclase-plagioclase abundances, a granodiorite (K/Ar age of 91.6 million years; Ref. 1). It resembles other intrusive rocks of north-western Nevada with no major petrographic differences. It comprises a horst block that rises 5000 feet above the valley floor at Gerlach. It is in intrusive contact with late Paleozoic (?) rocks in places.

The volcanic rocks bordering Hualapai Flat are of the Oligocene South Willow Formation (Ref. 2). The South Willow Formation is predominately intermediate to mafic volcanic flows and breccias. The formation unconformably overlies pre-Tertiary rocks near Cottonwood Creek and is overlain just to the west by Miocene-Pliocene volcanic rocks which represent the eastern border of the Modoc Plateau volcanic rocks. The Calico Mountain Range is predominantly intermediate flows, tuffs, and sedimentary rocks. The base of the sequence is not exposed and the top is an erosional surface. The youngest rocks of the area are several intrusive rhyolite plugs in the northwestern corner of Hualapai Flat which intrude the South Willow Formation. They can only be said to be post-South-Willow formation and probably late Miocene to Pliocene.

Quaternary deposits consist of Pleistocene Lake Lahontan deposits and Recent playa, dune, and alluvial sediments. Sizeable buildups of sinter are present around several hot springs and warm water wells.

Pre-Tertiary structure is obscured by the extensive volcanic cover and lack of Mesozoic and older rocks. The area marks the transition from a physiographic province where general Basin and Range faulting is obvious to the Modoc Plateau Province to the west, where continuous flows of basalt obscure the faulting to some extent. The area is seismically active and several faults have been mapped across Recent playa deposits with vertical offsets of up to ten feet.

III. INFRARED SURVEY

Airborne infrared scanning or mapping is potentially a powerful tool in prospecting for geothermal systems (Refs. 3, 4, and 5). The most impressive results have been obtained in neovolcanic areas where extreme variations in temperature exist at the earth's surface. Infrared imaging may also be of use in exploration in a basin and range setting in two ways; by providing an inventory of both thermal and normal spring activity, and by serving as an indicator of the location of fault traces at the earth's surface. In an arid region such as northwestern Nevada, many springs are intermittent, or discharge below the earth's surface. Such springs can alter the soil moisture sufficiently to affect the temperature or emissivity and cause a detectable change in thermodynamic temperature. Infrared imagery can then be used to locate hidden springs and water discharges to be sampled for geochemical studies.

An infrared survey was flown in early October, 1974, with the area being covered extending from the vicinity of Gerlach on the south to Soldiers Meadows on the north. The survey was flown by Earth Satellite Corporation, using a Daedalus scanner operating in the 8 to 14 micrometer wave-length band, and

flown at an altitude of 7500 feet above the land surface. The imagery obtained from the area immediately around the Fly Ranch hot springs is shown in Figure 3.

IV. MICROSEISMICITY STUDY

The author of Ref. 6 has reviewed evidence that there is a close association between locally intense microseismic activity and the occurrence of geothermal systems. The microseismicity of northwestern Nevada has been described in several papers (Refs. 7, 8, 9 and 10). However, coverage of the Gerlach - Fly Ranch area in these earlier studies was poor, and so, Microgeophysics, Inc., of Golden, Colorado, was engaged to carry out a microseismicity survey of the Black Rock Desert area. For this purpose, five high-gain (3 to 6 m), high-frequency (1 to 30 Hz) seismic arrays with a detection threshold below magnitude -1.0 were operated for a total of 30 days in May and June, 1974.

Each array operated with seven Sprengnether model MEQ-800-B portable seismic systems sited at separations of approximately 3 miles. Only vertical geophones were used; these were connected to a recording system which recorded on smoked paper at a chart speed of 120 mm/min. Each recording system had an integral timing system based on a precision clock synchronized daily with a WWVB signal. Arrival times for compressional waves were determined within ± 0.05 seconds. Almost all seismometer locations were on outcrops of crystalline or igneous rock. Station sites were moved during the course of the survey, so that the same seven recording systems were used to form the five arrays.

A total of approximately 420 local events and 111 teleseisms were identified during the 30 days of operation. All but 100 of the local events were observed on a single day, Julian day 169, 1974, in a concentrated swarm that occurred along the boundary between the Black Rock Desert on the east and the Granite Range block on the west. Prior to this day of swarm activity, the rate of occurrence of local earthquakes was approximately 2 per day. These events outlined activity along a line separating the Granite Range block from the Black Rock Desert, and along an east-west line passing through Hualapai Flat. This may be seen in Figure 4, a map showing contours of the cumulative amount of strain energy released during the 25 days preceding the swarm. The swarm occurred immediately to the southeast of the alkali flat in the southern end of Hualapai Flat, at the site of maximum strain rate prior to the swarm.

V. ELECTRICAL SURVEYS

Electrical resistivity surveys are accepted as being the most direct approach to locating reservoirs containing geothermal fluids (Ref. 11). An increase in rock temperature from a normal value of 20° to 60°C to an anomalous value of 200° to 300°C will evoke a five- to six-fold reduction in resistivity. A reservoir with sufficient volume to be of economic interest will provide a very large target for electrical prospecting techniques, unless the effect of

temperature is cancelled by compensating changes in water salinity or porosity. Such changes are unlikely.

Because of the size and large contrast in resistivity for a geothermal reservoir, any electrical surveying technique with the capacity to reach to depths of 5000 to 10,000 feet will be capable of detecting the reservoir. We have used the dipole mapping technique for reconnaissance, and this is to be followed by more definitive electromagnetic sounding surveys (Ref. 11) once the probable location of a geothermal reservoir has been determined.

In the dipole mapping survey, the concept is that a current field will be distorted by the presence of conductive masses of rock such as are associated with geothermal reservoirs. This distortion is mapped by measuring electric field intensity at many points around a single bipole current source. Areas of unusually low electric field intensity are normally assumed to be areas of unusually low resistivity. However, problems arise in this straightforward evaluation of dipole mapping surveys because in some cases, an area of anomalously low electric field intensity may appear without there actually being any subsurface region of low resistivity present. This occurs commonly at a fault-like boundary between a region with moderate resistivity values and another region with high resistivity values. In order to avoid being misled by such "false" anomalies, it is necessary to provide multiple coverage of an area in which an anomaly has been found, using several differently situated bipole sources. The rotating dipole method offers an approach to multiple coverage which is superior to the use of multiple but randomly located sources.

In the rotating dipole method, measurements of electric field intensity are made at a receiver location as a function of the orientation of the source wire as the source wire is swung through a 360° rotation. As the source rotates, the direction of current flow at the receiver site will rotate through all possible directions, and apparent resistivity values which are maximally and minimally affected by boundaries in actual resistivity will be measured. The field procedure consists of making only two sets of electric field measurements at a receiver site, one for each of two orientations of the source wire. Then, the two electric field vectors can be added in the proper proportions to determine the apparent resistivity for any orientation of the source bipole.

Rotating dipole surveys were carried out in the Fly Ranch - Gerlach area using five sets of bipole sources. Each bipole source was one mile in length, and powered with current steps with amplitudes ranging from 40 to 120 amperes. The current waveform was that of an asymmetrical square wave, with a repetition rate of 3 per minute. Measurements of electric field strength were made at 320 receiver sites, at distances from the bipole source ranging up to 5 miles.

Many different resistivity values can be computed from the data obtained in a rotating dipole survey, but computations made for various theoretical models suggest that the best value is an average of the maximum and minimum apparent resistivities obtained on rotation. A contour map of averaged maximum and minimum resistivities measured from one pair of bipole sources is shown in Figure 5. The sources are located in the Black Rock Desert, immediately south of the Hualapai Flat area, and over the epicenters of the majority

of the earthquakes detected during the microseismicity survey. An area of extremely low resistivity is present at the contact between the bedrock saddle and the Black Rock Desert sediments, with values of less than 1 ohm-meter being observed. Within the bedrock to the north, extending into Hualapai Flat, apparent resistivities remain moderately low, being about 20 ohm-meters along the trend of the hot spring activity.

VI. SUMMARY

Ample evidence exists for a geothermal system at Fly Ranch. Some of the most persuasive evidence is the surface expression of heat flow, represented by hot springs at or near the boiling point, and widespread areas of warm water seepage, seen on the infrared imagery. That this is not some random surface manifestation of structurally controlled ground water flow along a fault system is the evidence for an extensive reservoir at depth provided by the electrical resistivity surveys. The seismic activity along faults bounding the area of low resistivity suggests that high temperatures at depth have raised the pressure of pore fluids above normal. On the other hand, the geophysical and geological studies have not yet provided evidence for a local heat source at depth.

Additional detailed geophysical and geological studies must be carried out to evaluate the potential of the geothermal system properly. However, it will be necessary to drill at least one test well to determine the effectiveness of the exploration procedures.

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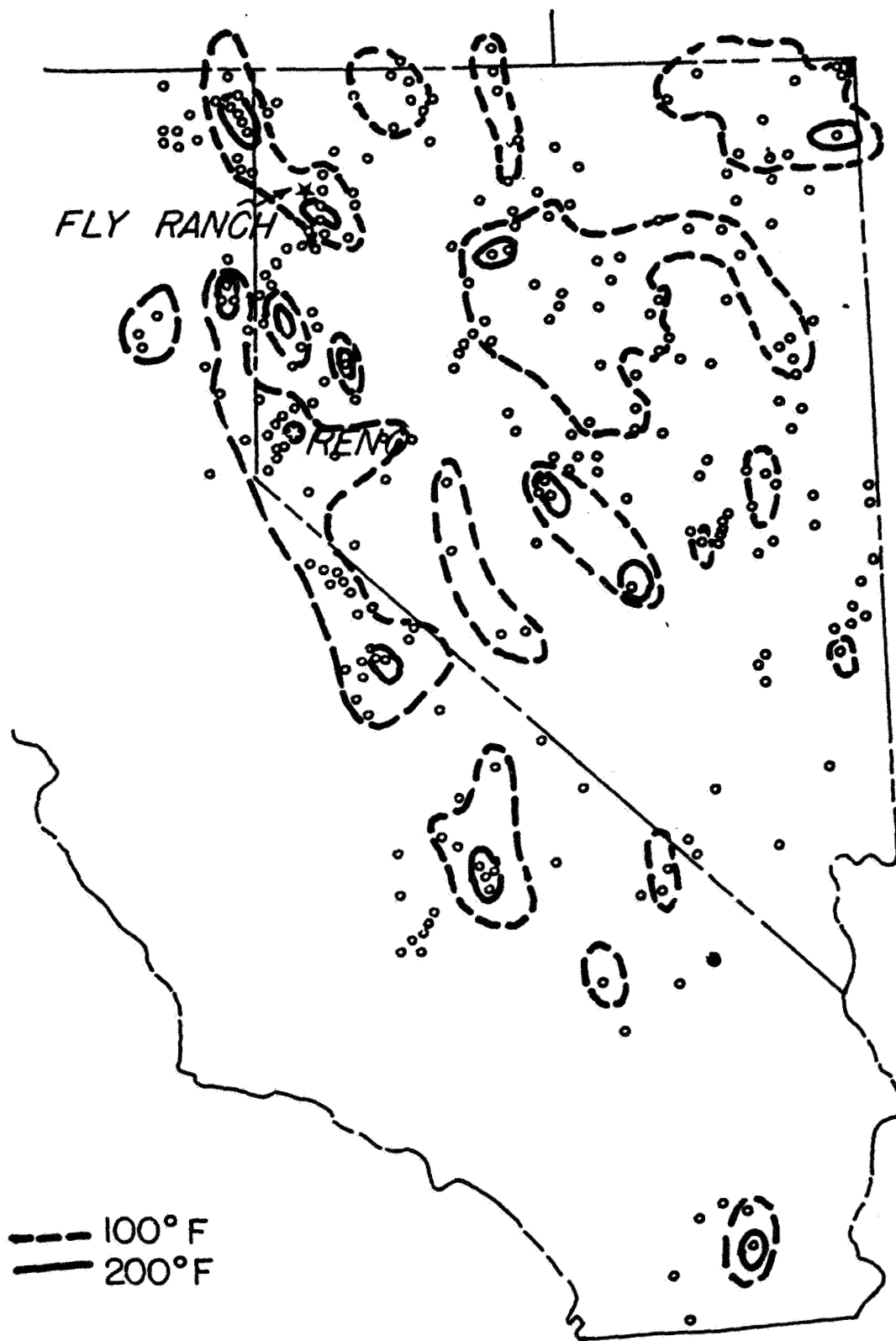


Fig. 1. Contours of thermal spring temperatures in the Basin and Range Province in Nevada and California

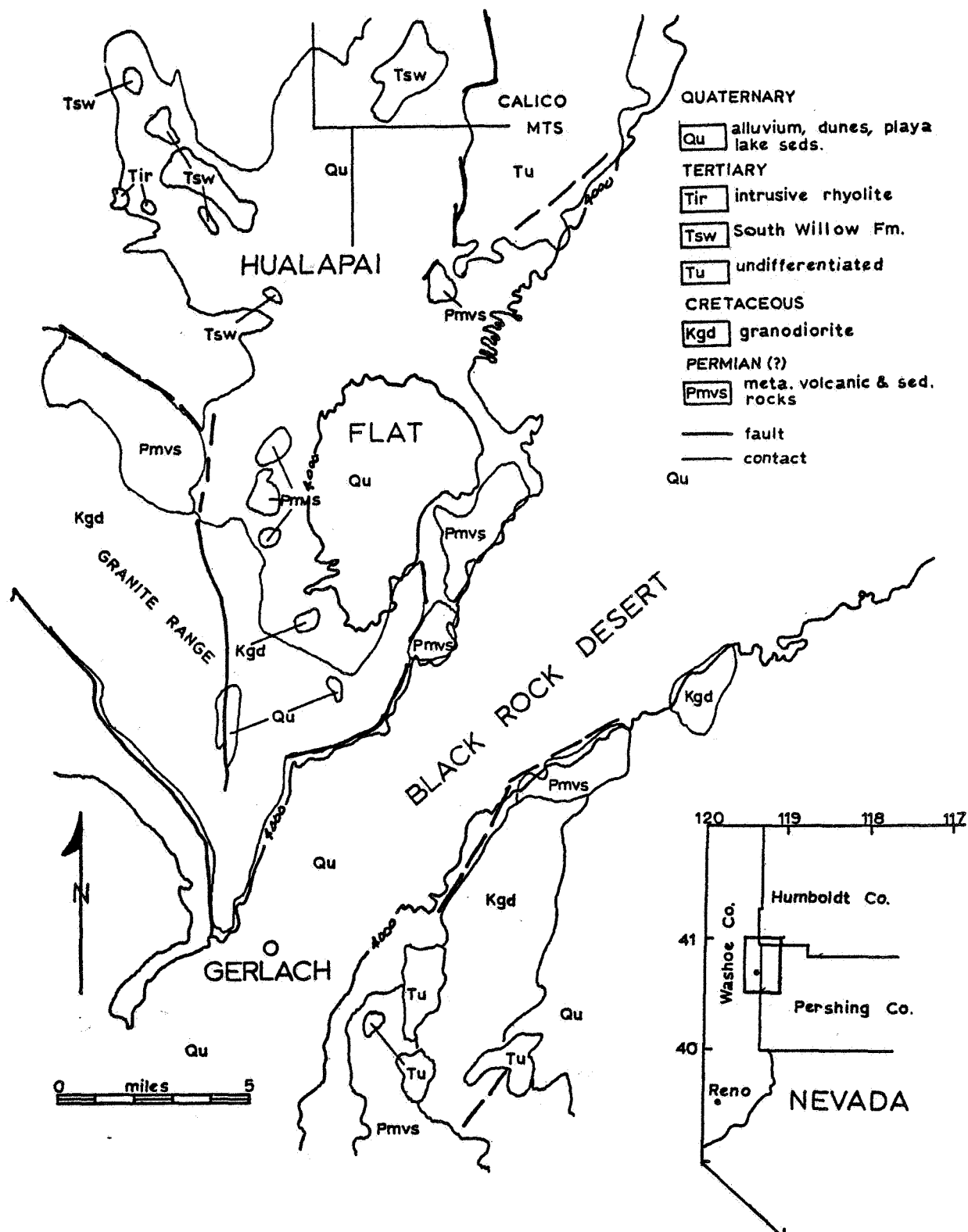


Fig. 2. Reconnaissance geological map of the Black Rock Desert area of northwestern Nevada



Fig. 3. Infrared imagery of the vicinity around the Fly Ranch hot springs, northern Nevada

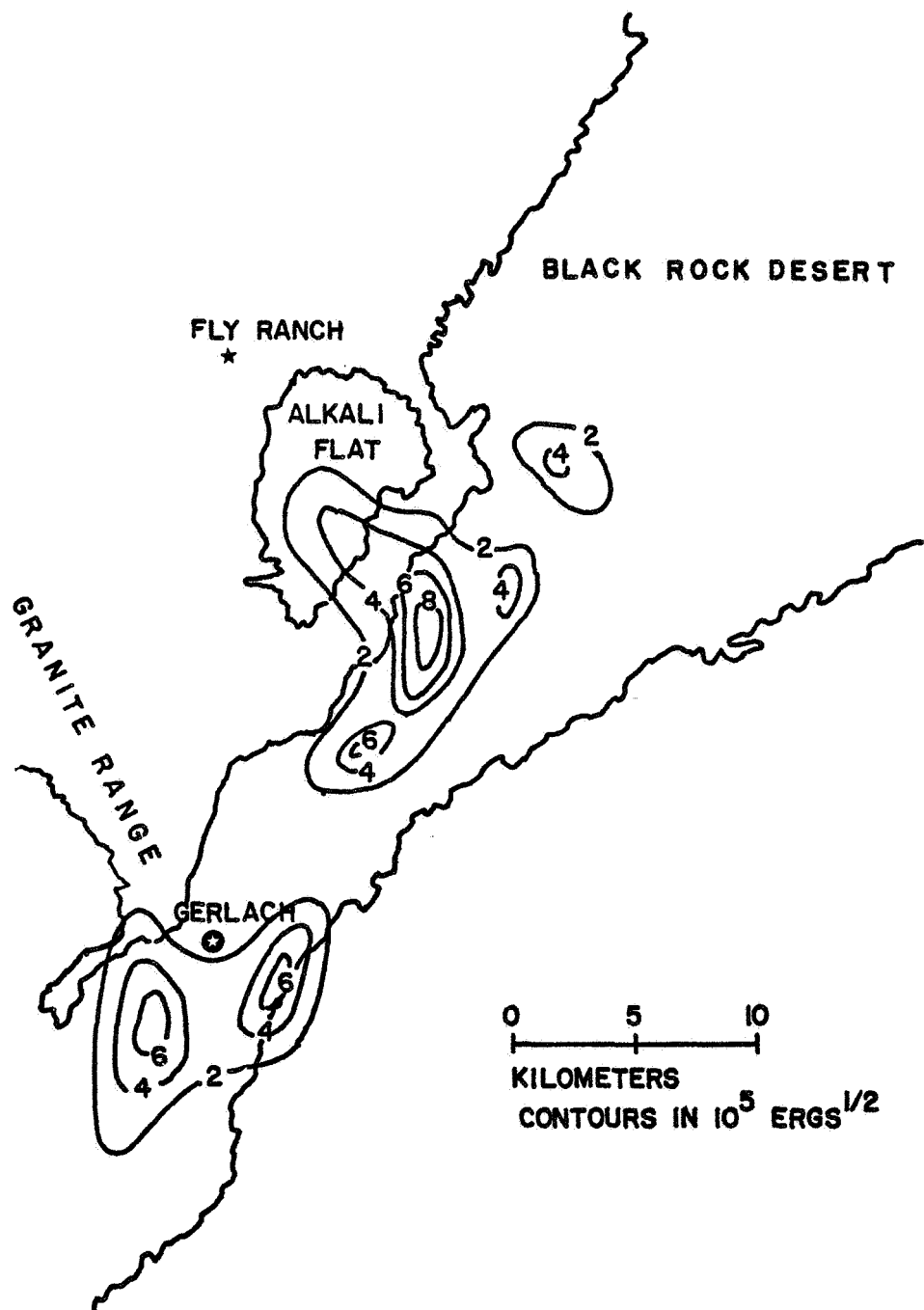


Fig. 4. Strain release for a twenty-five day period in the Black Rock Desert

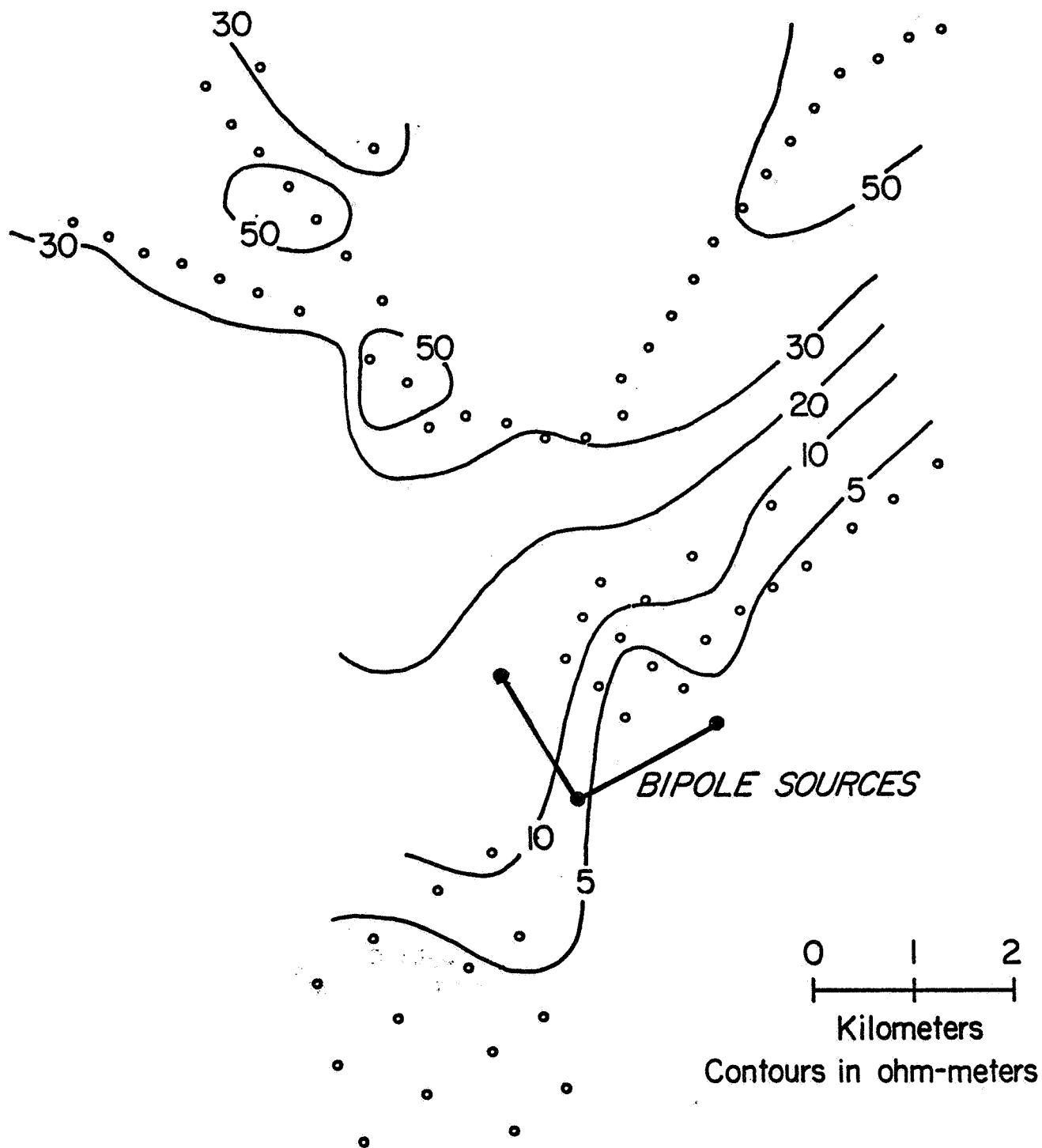


Fig. 5. Example of a rotating dipole resistivity survey at the western edge of the Black Rock Desert

HEAT FLOW AND GEOTHERMAL POTENTIAL
OF THE EAST MESA KGRA,
IMPERIAL VALLEY, CALIFORNIA

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The East Mesa KGRA (Known Geothermal Resource Area) is located in the southeast part of the Imperial Valley, California, and is roughly 150 km² in areal extent. A new heat flow technique which utilizes temperature gradient measurements across "best clays" is presented and shown to be as accurate as conventional methods for the present study area. Utilizing the "best clay" gradient technique, over 70 heat flow determinations have been completed within and around the East Mesa KGRA. Background heat flow values range from 1.4 to 2.4 hfu (1 hfu = 10⁻⁶ cal/cm²-sec) and are typical of those throughout the Basin and Range province. Heat flow values for the northwest lobe of the KGRA (Mesa anomaly) are as high as 7.9 hfu, with the highest values located near gravity and seismic noise maxima and electrical resistivity minima. An excellent correlation exists between heat flow contours and faults defined by remote sensing and microearthquake monitoring. This correlation indicates a tectonic origin for this lobe of the KGRA. The 5-hfu contour, which roughly defines the area in which a successful geothermal well can be completed, includes 40 km² of the northwest lobe of the KGRA.

Heat flow data for the southeast lobe of the KGRA (Border anomaly) are less reliable than for the northwest lobe and meaningful contouring is not possible. Maximum values are in the range 5-7 hfu and encompass an area of about 15 km². The center of the anomalous heat flow zone is on strike with the NW-SE trending fault located on the northwest lobe of the KGRA on the basis of microseismic monitoring, but is about 5 km south of the anomaly as defined on the basis of seismic groundnoise and electrical resistivity.

Previously unpublished heat flow data are also available for the Alamo geothermal anomaly, located about 15-20 km southwest of the East Mesa KGRA. Heat flow values are as high as 4.6 hfu, with the highest values located on either side of the Imperial Fault near the international boundary.

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I. INTRODUCTION

Heat flow is defined by the equation

$$q = -K \frac{dT}{dZ}$$

where q is heat flow, K is thermal conductivity, dT/dZ is the geothermal gradient, and the negative sign implies that heat flows from high temperature regions to those of low temperature. Thus the determination of heat flow requires knowledge of the geothermal gradient and the thermal conductivity of the strata over which the geothermal gradient is measured. The standard techniques for measuring geothermal gradient, thermal conductivity and the methods of obtaining heat flow and assessing the associated errors are summarized by Beck (Ref. 1).

The Imperial Valley, however, provides some interesting problems which make the standard heat flow techniques very difficult to apply. Most of the rock material in the Imperial Valley consists of unconsolidated sand, silt, and clay material so that collection of samples for thermal conductivity analysis is very difficult. Core samples suitable for measurement with a divided bar apparatus (Ref. 2) are virtually nonexistent and even collection of well cuttings for transient measurement (Ref. 1) or steady-state measurement (Ref. 3) provide problems. For example, there is always a tendency to preferentially sample clays because of their more consolidated nature and the uphole sloughing of material can substantially contaminate a sample. Also, the best thermal conductivity results are always obtained when laboratory analyses are performed under in situ conditions (Ref. 4) and for saturated sediments from geothermal areas; such conditions are difficult to reproduce in the laboratory, particularly when in situ temperatures exceed 100°C.

Because of the nature of the sediments and the abundance of wells in the Imperial Valley which are available for temperature measurement but had no core material available for conductivity analysis, it was decided to search for a method of obtaining heat flow without the need to make laboratory analysis of thermal conductivity. In the following sections, the resulting heat flow technique will be described and some of the problems associated with its application will be discussed. Finally, an analysis of the distribution of heat flow at the East Mesa KGRA will be presented.

II. HEAT FLOW TECHNIQUE

The heat flow technique developed for use at the East Mesa KGRA utilizes an empirical relation between known heat flow and temperature gradient measured across the "best clay," a stratigraphic horizon herein defined as that 10-foot section of a given well associated with the maximum temperature gradient and physically consisting of poorly conductive clay minerals and interstitial water, but having a minimum amount of highly conductive quartz. Figure 1 shows the relation between temperature gradient and lithology as

depicted by a gamma ray log for three wells drilled on the Mesa anomaly. Although these three wells are typical of those drilled at the Mesa anomaly, they were not selected for representation in Fig. 1 for that reason. Rather, these three wells were selected because they are the only wells on the Mesa anomaly for which gamma ray logs, detailed temperature gradient measurements, and heat flow data are all available, the latter having been independently determined by Combs (Ref. 5) using standard laboratory techniques. Notice the direct correlation between the plots of temperature gradient and gamma radiation in Fig. 1. The sands appear on both plots as lows, whereas the clays appear as highs. Numerical values of temperature gradients for several clays are shown in Fig. 1, and the "best clay" (i.e., the maximum gradient) is designated with lined pattern.

Figure 2 is the heat flow calibration chart and is the basis of the present heat flow technique. Plotted in Fig. 2 is known heat flow (Ref. 5) as a function of the "best clay" gradient (Fig. 1). The following steps then summarize the method used herein to determine heat flow in the sand-clay sequences of the Imperial Valley:

- (1) Measure temperatures to an accuracy of 0.01°C at 10-foot intervals throughout the well.
- (2) Calculate the temperature gradient for each 10-foot interval and designate the maximum gradient as the "best clay" gradient.
- (3) Make use of available geophysical logs to insure that the maximum temperature gradient actually falls opposite a clay horizon and does not result from measurement error or groundwater circulation.
- (4) Use the linear plot of Fig. 2 to convert the "best clay" gradient to heat flow.

The accuracy of the present heat flow technique can be assessed from the data in Fig. 2. As long as a straight line can be drawn to fit all data points to within the error limits of the heat flow values, the technique is working as well as conventional methods. For the present study, an error of 0.3 hfu is suggested, an error which primarily reflects the errors associated with the control heat flow values (Fig. 2), rather than the internal consistency of the present technique. A more accurate heat flow calibration chart based on additional measurements of thermal conductivity is currently in preparation (Ref. 6). This newer calibration will slightly affect the heat flow values shown in Fig. 4, but not to the extent of the above stated accuracy. Also plotted against heat flow in Fig. 2 are the average geothermal gradients. The scatter of data underscores the inherent limitations of average geothermal gradients as a geothermal exploration tool and emphasizes the increased resolution that results from the present technique.

There are several interesting features of Fig. 2 that bear special mention. The reason that heat flow is a linear function of "best clay" gradient and the success of the technique is due to the fact that all of the "best clays" have the same thermal conductivity. This is a rather stringent requirement, particularly over large geographic areas and emphasizes the danger in attempting to apply the calibration curve of Fig. 2 to widespread parts of the Imperial Valley.

However, the data in Fig. 2 clearly shows that this requirement is quite realistic over the limited area surrounding the East Mesa KGRA. Clearly the present heat flow technique cannot be applied to regions other than those comprised of sand, silt, and clay continental sediments, such as those in the Imperial Valley.

Figure 2 is a plot of heat flow against temperature gradient so that the slope of the heat flow calibration line must represent thermal conductivity. The slope of the line in Fig. 2 is $2.41 \text{ cal/cm-sec-}^\circ\text{C}$, a very realistic conductivity value for clay material.

The "best clay" gradients in Fig. 2 represent average gradient over a 10-foot section of clay, and this measurement interval should be used in determination of heat flow using Fig. 2. Clearly, a calibration curve similar to Fig. 2 can be constructed for any measurement interval, simply by measuring temperatures at that interval and plotting the resulting "best clay" gradients against known heat flow. However, a larger interval, such as temperature measurements every 50 feet, requires rather thick clay horizons which may not exist in a given stratigraphic section (see following section), whereas a smaller interval, such as measurements every 2 feet, requires more accurate temperature measurements (particularly in nongeothermal areas) and additional field time to make the measurements. Although the smaller interval should result in a more accurate heat flow calibration, the calibration shown in Fig. 2 is sufficiently accurate for the present study in view of the rather large errors associated with the known heat flow values. A measurement interval of 10 feet was found to give the most satisfactory results of the several intervals examined.

III. DISCUSSION OF THE "BEST CLAY" HEAT FLOW TECHNIQUE

The greatest advantage of the present heat flow technique is that it does not require the time-consuming and costly laboratory determination of thermal conductivity and thus makes available for heat flow analysis the wealth of drill holes in the Imperial Valley which are available for temperature gradient measurements, but which have no associated core material for thermal conductivity analysis. There is also a logistical advantage in the present technique in that heat flow values can be obtained in the field and thus correlated directly with any geological observations that may pertain to geothermal studies.

Another important feature of the "best clay" approach is that maximum interpretative value of temperature data is obtained. Since all of the "best clays" have very nearly the same thermal conductivity, a contoured map of "best clay" gradients will have precisely the same form as a contoured heat flow map, the only difference being the numerical value and units of the contours. Thus, the "best clay" technique is a useful method of geothermal exploration even in areas where a lack of heat flow data precludes the construction of a heat flow calibration chart such as Fig. 2.

The principal drawback to the present technique is the difficulty in assessing the error associated with a given heat flow value. It is of little use to apply statistical methods to the data in Fig. 2 because any resulting standard deviation would reflect the error only if a "best clay" is present, and there is unfortunately no way to guarantee the presence of such a clay. Figure 3 shows a plot of

temperature gradient against lithology as depicted by resistivity, lithologic, and gamma ray logs for well T. 16 S., R. 18 E., 23aaa, located several kilometers northeast of the East Mesa KGRA. The heat flow technique presented above does not yield a suitable estimate of heat flow for this well, and the reason is simply that a "best clay" does not exist. Examination of the lithologic log, for example, shows the entire well to consist of sand with only 5 clay stringers, ranging in thickness from 2-8 feet. These clays are contrasted with those present in wells 123-125 (Fig. 1), which are in excess of 50 feet thick. Further, the thickest clay in well 23aaa consists of 30 percent gravel, 10 percent quartz, along with appreciable calcite, so that in addition to having an insufficient thickness for the application of the "best clay" heat flow technique, the clays are also of the wrong composition. Since there is generally no way of determining the presence or absence of the required clay horizons from a temperature survey alone, it is imperative that a good suite of logs be available for correlation with temperature gradient data. If a suite of logs is available along with the temperature gradient data, it should be possible to determine the presence or absence of the required "best clay" and thus estimate the reliability of a given heat flow value. Of the more than 70 wells used in the present heat flow study, only two do not have the required clay horizons, and these are designated in Fig. 4 with a heat flow value of "low."

In the case of well 23aaa, the absence of suitable clay material and the failure of the "best clay" heat flow technique can be determined even without the associated geophysical and lithologic logs, although this is not always or even generally the case. As shown in Fig. 3, the "best clay" has a gradient of only 24°C/km. Using this value to obtain a heat flow value from Fig. 2 gives a heat flow value of very nearly zero. Such a value is obviously unrealistic so that an error somewhere is suspected. The excellent correlation between lithology and temperature gradient (Fig. 3) suggests that the hole is in thermal equilibrium, and problems such as groundwater circulation or measurement error are not responsible for the low heat flow value. In fact, the data in Fig. 3 shows quite clearly that the unreasonably low heat flow value results from the lack of a "best clay" and the associated failure of the present heat flow technique to apply to this well.

IV. HEAT FLOW AT THE EAST MESA KGRA

The distribution of heat flow values over and adjacent to the East Mesa KGRA is shown in Fig. 4. Background heat flow values range from 1.4 to 2.4 hfu (1 hfu = 10^{-6} cal/cm²-sec) and are typical of those throughout the Basin and Range physiographic province (Ref. 7). Over the northwest part of the KGRA (Mesa anomaly) values are as high as 7.9 hfu, while over the southeast part of the KGRA (Border anomaly) values are as high as 7 hfu.

The three pronounced contours of Fig. 4 are the 3-, 5-, and 7-hfu contours. The 3-hfu contour roughly outlines the extent of anomalously high heat flow. Areas outside this contour are only marginally above the regional background and such areas cannot be expected to yield successful production wells, although such areas might well prove ideal for disposal of geothermal brine. The area within the 5-hfu contour can be considered the production area. Anywhere within this contour should yield a successful production well,

provided, of course, that suitable producing horizons are encountered. For the East Mesa KGRA, roughly 55 km² or 21 square miles of land fall within this contour.

Also shown in Fig. 4 are the three faults postulated for the East Mesa KGRA. One of these faults (Ref. 8) is currently active and was located during microseismic monitoring at the Mesa anomaly. The correlation between the faults and the heat flow contours is obvious, and this correlation indicates a tectonic origin for both lobes of the East Mesa KGRA. That is, the faults act as conduits, allowing the rise of geothermal fluids from the deep igneous heat source into the geothermal reservoir. Note also that for the northwest lobe of the KGRA, heat flow values decrease with distance very rapidly west of the zone of maximum heat flow, but decrease very slowly to the east. This indicates that the northwest trending faults either dip to the east or alternately that the predominant flow of water in the geothermal system is to the east, away from the faults.

The heat flow values for the southeast lobe of the KGRA are shown in Fig. 4 with an order of magnitude lower accuracy than the remaining values. This lower accuracy is presented because several of the wells exhibit temperature reversals below 500 feet, and, since no deep geothermal wells have been drilled into this portion of the KGRA, the existence of a geothermal reservoir has not yet been established.

Also presented in Fig. 4 are heat flow values for the Alamo anomaly, a part of the Heber KGRA. The highest values are roughly 4.5 hfu and fall on opposite sides of the Imperial fault. These values are included to demonstrate that geothermal activity is also associated with the Imperial fault.

Figure 5 shows the maximum contours of all geothermal exploration techniques that have been applied to the East Mesa KGRA. From a standpoint of exploration, the northwest part of the KGRA is an ideal place to evaluate the reliability of various geothermal exploration techniques. Not only has every technique applied been successful, but each method gives essentially the same result, although they differ in detail. If production wells were to be located on the basis of heat flow, residual gravity, seismic noise, microearthquake epicenters, or electrical resistivity, the holes would all fall within a few hundred meters of one another and all would fall within the zone suitable for geothermal development as defined by the 5-hfu contour. Also note the 5-hfu heat flow contour agrees well with the anomalous zones defined by the dipole-dipole resistivity soundings. Resistivity is a difficult exploration technique to apply to the Imperial Valley because the contrast between geothermal areas and adjacent colder areas is so low. This low contrast may preclude reliable modeling on the basis of the resistivity data, but the information presented in Fig. 5 clearly indicates that resistivity is a valuable tool in the Imperial Valley for outlining zones of anomalously high subsurface temperatures.

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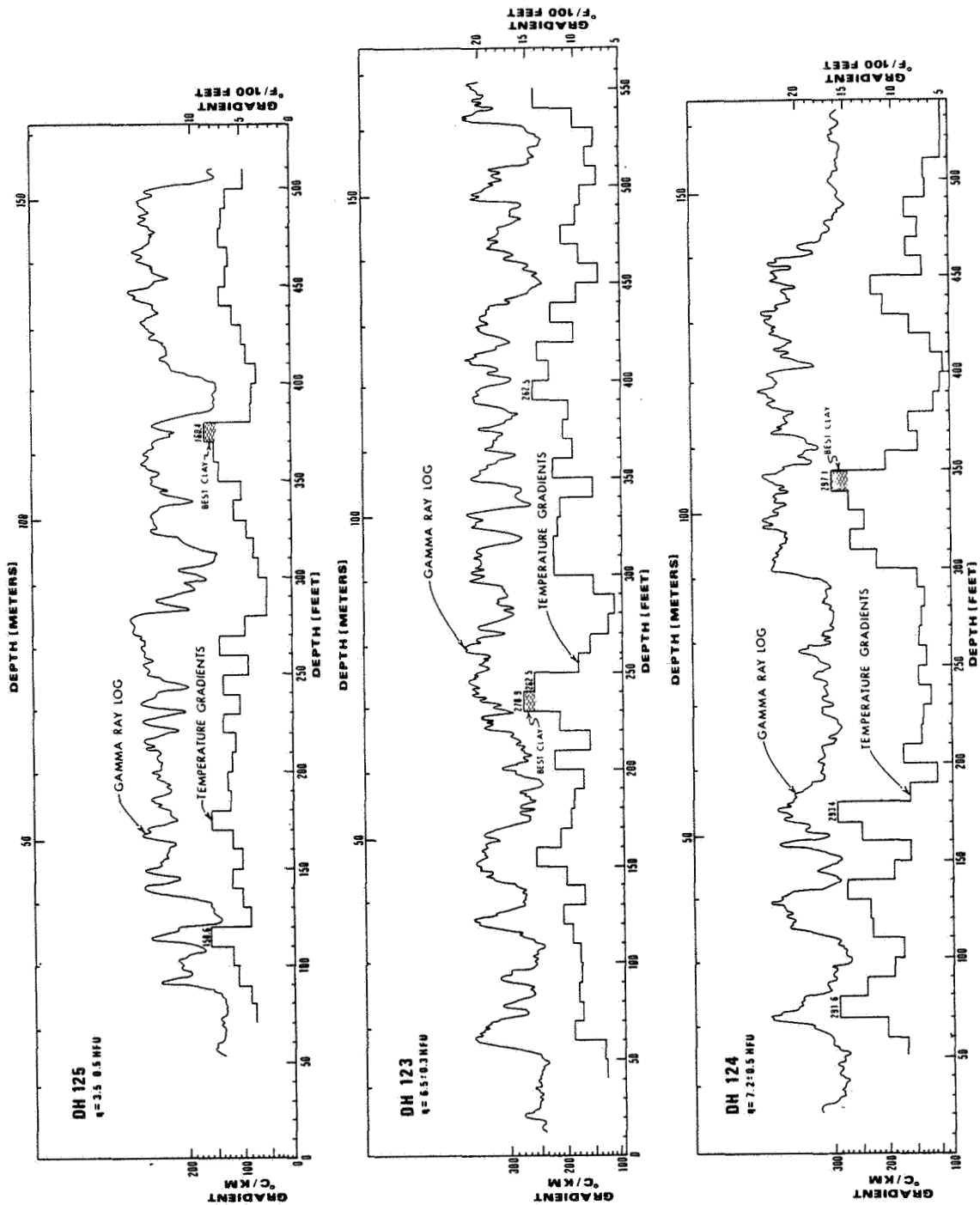


Fig. 1. Relation between temperature gradient and lithology as depicted by a gamma ray log for drill holes 123-125. The "best clays" are designated by the lined pattern.

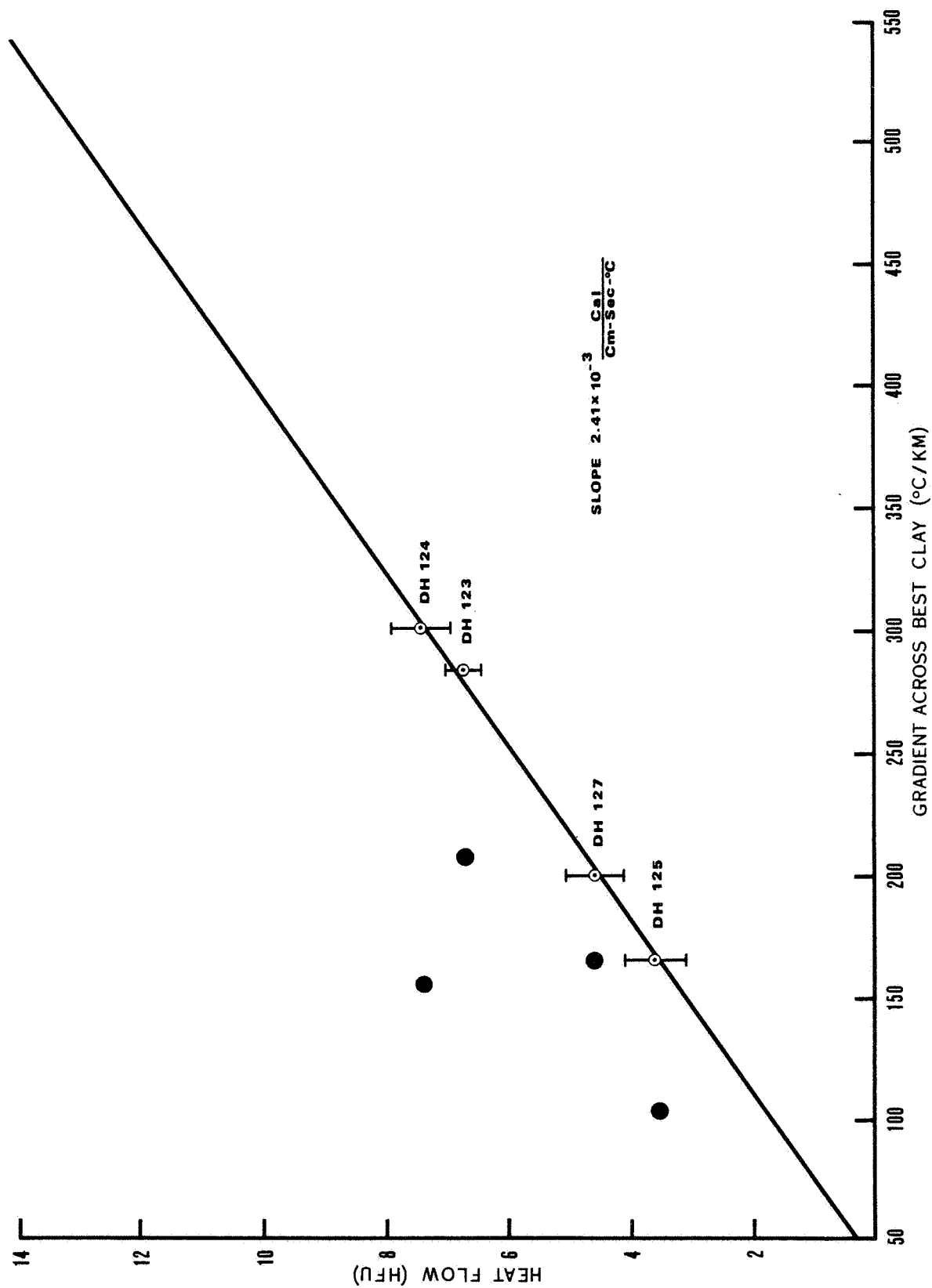


Fig. 2. Relation between heat flow and "best clay" temperature gradient. The solid dots represent the average gradient over the entire hole (see text).

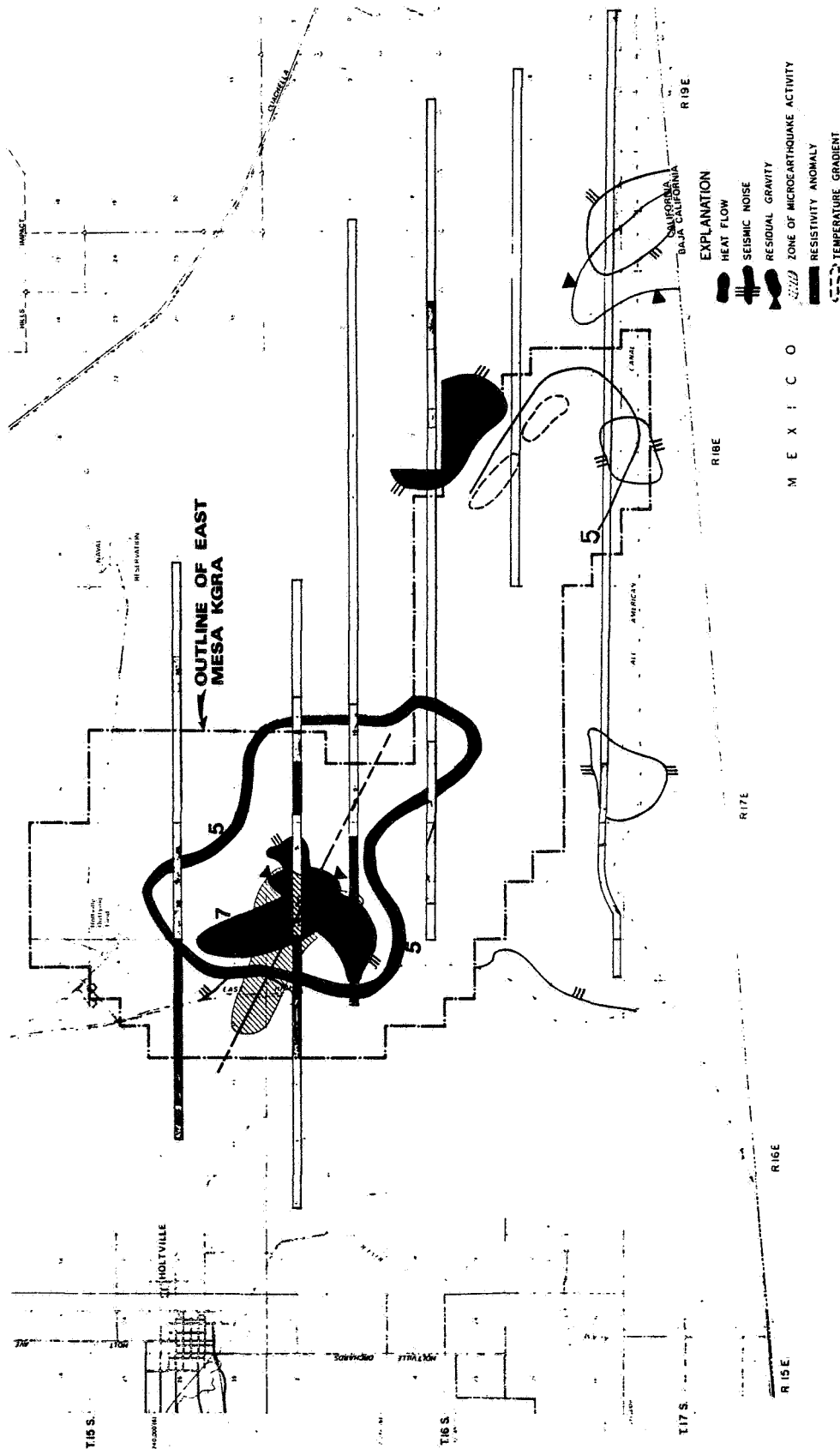


Fig. 5. Summary of geophysics at the East Mesa KGRA. Gravity data are from Biehler (Ref. 9) and shows maximum residual anomaly (solid with triangles) for the northwest lobe and maximum Bouguer gravity (open with triangles) for the southeast lobe of the KGRA. Seismic noise maxima (Teledyne-Geotech) are open when possibly related to cultural activity and solid when related to geothermal activity. Resistivity profiles (McPhar Geophysics) show confirmed anomalies (solid) and suspected anomalies (gray). Temperature gradient data is from Combs (Ref. 10) and microseismic data is from Combs and Hadley (Ref. 8).

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A BRIEF DESCRIPTION OF GEOLOGICAL AND GEOPHYSICAL
EXPLORATION OF THE MARYSVILLE GEOTHERMAL AREA

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Extensive geological and geophysical surveys were carried out at the Marysville geothermal area during 1973 and 1974. The area has high heat flow (up to $20 \mu\text{cal}/\text{cm}^2\text{-s}$), a negative gravity anomaly, high electrical resistivity, low seismic ground noise, and nearby microseismic activity. Significant magnetic and infrared anomalies are not associated with the geothermal area. The geothermal anomaly occupies the axial portion of a dome in Precambrian sedimentary rocks intruded by Cretaceous and Cenozoic granitic rocks. The results from a 2.4-km-deep test well indicate that the cause of the geothermal anomaly is hydrothermal convection in a Cenozoic intrusive. A maximum temperature of 95°C was measured at a depth of 500 m in the test well.

I. INTRODUCTION

The Marysville geothermal area is located about 30 km northwest of Helena, Montana, and about 4 km west of the old gold mining town of Marysville, Montana. The Continental Divide crosses the southern part of the area, so the terrain is mountainous, with a local relief in excess of 600 m (Fig. 1). The area had an extensive history of gold mining during the late 1800's and early 1900's. In the 1960's, the area was explored for disseminated molybdenum deposits by drilling at two locations. The existence of a geothermal anomaly in the area was discovered in 1966 during a regional heat flow study. Very high heat flow ($6.5 \mu\text{cal}/\text{cm}^2\text{-s}$) was measured at one of the sites of molybdenum exploration (the Bald Butte locality, Ref. 1). Subsequent measurements at the second molybdenum exploration site (Empire Creek) and in some holes drilled for gold exploration during the 1950's (Woodchopper Gulch and Ottawa Gulch localities) indicated heat flow values from 3.3 to $20 \mu\text{cal}/\text{cm}^2\text{-s}$, over an area of several square kilometers (Ref. 2). The average background heat flow for western Montana is approximately $2.0 \mu\text{cal}/\text{cm}^2\text{-s}$, while the world average heat flow is about $1.5 \mu\text{cal}/\text{cm}^2\text{-s}$. Thus, the heat flow in the area is up to 10 times the already high background observed in western Montana.

Subsequent to the discovery of the geothermal anomaly, a detailed gravity study was carried out in the area by Mazzella (Ref. 3). Analysis of data from

this survey indicated a negative gravity anomaly, and thus a region of mass deficiency, associated with the high values of heat flow. The correlation of a region of relatively low density with one of high heat flow was considered suggestive that the source of both anomalies might be a relatively shallow (<2 km) cooling chamber of recently molten igneous rock. Thus, extensive further geological and geophysical investigations were begun in 1973 in order to investigate the area in detail.

The Marysville geothermal area is unusual because, although the geothermal gradient is as high as 240°C/km, there are no surface manifestations of the anomaly. The hot spring nearest the geothermal area is 30 km away (the Broadwater Hot Spring, just west of Helena, Montana). The nearest recent volcanics are over 300 km away at Yellowstone National Park. Furthermore, the Precambrian sedimentary rocks and Mesozoic and early Cenozoic intrusive rocks of the area seem an unusual setting for a geothermal anomaly.

The geothermal reservoirs currently being exploited commercially have few common geological characteristics. For example, the Geysers field is in fractured graywacke and siltstones, the Larderello field is in carbonate rocks, the Wairakie field is in volcanic rocks, and the Imperial Valley and Cerro Prieto fields are in alluvial and deltaic sediments (Refs. 4 and 5). Similarly, the geophysical characteristics of these geothermal areas vary widely. Discussions of exploration techniques emphasize flexibility in the approach to geothermal exploration (Refs. 6 and 7). Study of the Marysville area was undertaken to provide a case history of geothermal exploration in an area with few surface clues, and to furnish deep hole data for comparison with surface geological and geophysical studies.

The studies carried out in the Marysville area have included geologic mapping, petrographic and chemical analyses, spring-water chemistry, gravity, magnetic heat flow, seismic ground noise, microearthquake, dipole-dipole resistivity, magnetotelluric and audio-magnetotelluric, and airborne infrared studies. During the summer of 1974, a 2.4-km-deep exploration hole was drilled to test the geothermal area at depth and the implications of the geological and geophysical studies. The results of these studies will be summarized briefly.

II. REGIONAL SETTING

The Marysville area is in the Northern Rocky Mountains physiographic and structural province (Ref. 8) and is about 40 km west of the extensive zone of large-scale thrust faulting (Ref. 9), which generally marks the eastern boundary of the Northern Rocky Mountains. Some of the thrust faults have displacements of tens of kilometers and could conceivably underlie the Marysville district. The country rocks of the district are Precambrian sedimentary rocks of the extensive Belt Series terrain of western Montana (Ref. 10). There has been extensive plutonic activity in the area and the large Boulder batholith (Ref. 11) of late Cretaceous age outcrops only 20 km south of the area (Ref. 12).

III. GEOLOGY

The geology in certain parts of the geothermal area has been studied in the past. An early study of the eastern part of the area by Barrell (Ref. 13) focused on the geology of the Marysville mining district as did the study of Knopf (Ref. 14). Bierwagen (Ref. 15) mapped a large area from Blossberg (10 km south of Marysville) to Lincoln, with particular emphasis on the stratigraphy of the sedimentary rocks. Ratcliff (1973, personal communication) studied an area which included the geothermal anomaly with a special emphasis on the bulk chemistry of the igneous rocks.

A. Sedimentary Rocks

The two formations which occupy most of the area on the geologic map (Fig. 1) are the Helena Limestone and the subjacent Empire Shale. Both formations are part of the Precambrian Belt Series, which is extensively exposed in northwestern Montana (Ref. 10). The Empire Shale is a biotite-rich siliceous to calcareous shale, and the Helena Limestone consists of siliceous limestone and dolomite with occasional interbeds of quartzite and shale. Other sedimentary rocks exposed in the area include the Spokane Shale, a purple to gray-green argillite, below the Empire Shale, and the Marsh Shale, a red to maroon argillite unit, the Greenhorn, and the Black Mountain Quartzites, above the Helena. Lower Paleozoic to Cretaceous units unconformably overlie the Belt rocks in a major syncline southwest of the geothermal area.

The geologic map (Fig. 1) incorporates the published work, but with significant modifications. In much of the area, the Helena and Empire have been contact metamorphosed into calcsilicate hornfels (Refs. 13 and 14) and are very difficult to distinguish. Detailed x-ray and petrographic studies of the contact metamorphic assemblages characteristic of each unit have resulted in criteria for differentiation of the two units, however, and their distributions are somewhat different than published mapping would suggest.

B. Contact Metamorphism

A broad zone of contact metamorphism extends to the southwest of the stock, as is indicated by the location of the diopside isograd (Fig. 2). Two other contact metamorphic zones with diopside grade metamorphism (the estimated temperature was 500°C at 750 bars) occur in the vicinity of Bald Butte and in Empire Creek. Exploration drilling at Bald Butte and in Empire Creek has intersected unexposed quartz porphyry intrusives beneath each of these contact zones. The large areas of contact metamorphism imply a much larger size for each of these quartz porphyries than is established by drilling. These two intrusive bodies occupy the dome in the sedimentary rocks southwest of the Marysville stock.

C. Igneous Rocks

The igneous history of the Marysville area has been quite complex. A summary of that history is shown in Table 1. The oldest igneous rocks are microdiorite sills in the upper part of the Empire Shale. These sills may be correlatives of the gabbro or diabase sills regionally developed at that stratigraphic horizon which have been dated as Precambrian. The next dated igneous

event was the emplacement of the Marysville granodiorite at approximately 79 M. Y. B. P. (Ref. 16) as one of the early satellitic phases of the Boulder Batholith.

There appear to be at least two Tertiary igneous events, although the dating is preliminary (Rostad, personal communication, 1971; Ratcliff, personal communication, 1973). The intrusion of the Bald Butte quartz porphyry has been dated at 49 M. Y. B. P., but the most extensive activity apparently occurred between 37 and 40 M. Y. B. P. Numerous feldspar porphyry dikes and sills were emplaced during this episode, concentrated in an area southwest of the Marysville stock; a large (presently unexposed) quartz-feldspar porphyry body was intruded (the Empire stock), also in the area southwest of the Marysville stock; and extensive rhyolite flows and tuffs were extruded along a north-south axis west of the Marysville stock and over an area several tens of kilometers long. Considerable erosion has occurred since the episode of volcanism, and the present exposures are relatively isolated, but the volcanics may have been much more extensive in the past.

D. Structure

There have been several episodes of deformation in western Montana, and it is difficult to sort out the relative ages of the folds and faults in the Marysville area. The folds are mostly large-scale, open features. The basic structure of the map area is a dome in the sedimentary rocks. The core of this dome is shown on the geologic map by the exposures of the Empire Shale and Marysville stock. The northeastern half of the dome is occupied by the Marysville stock, and that portion of the dome may be related to the emplacement of the stock. The geothermal anomaly occurs in the southwestern portion of the dome. There is a pervasive fracture cleavage developed in most of the Belt rocks with general north-south orientation and west dip.

The contact metamorphic aureole of the Marysville stock has been offset in at least one location by faulting (near the Empire Mine), so some of the faulting is definitely post-79 M. Y. B. P. The area is still the site of tectonic activity, demonstrated by the occurrence of microearthquakes.

IV. GEOPHYSICS

A. Magnetic Surveys

The magnetic surveys (both ground and airborne studies) indicate anomalies associated with variations in the content of magnetic material in the rocks. Because igneous rocks usually contain more magnetic material than sedimentary rocks, magnetic anomaly maps commonly contain information on the distribution of igneous units in the map area. In the Marysville district, the only significant magnetic anomaly is associated with the Marysville stock. The quartz porphyries of Bald Butte and Empire Creek do not have significant anomalies. A model of the Marysville stock was developed from the data using the numerical technique of Talwani (Ref. 17). Two contours plus the outcrop trace of the stock are shown in Fig. 2.

B. Electrical Surveys

A roving dipole resistivity survey was done by the U. S. Geological Survey in 1972. The results of that survey indicate rather high resistivities of 150-1000 Ω -meters associated with the geothermal anomaly. Similarly, a magnetotelluric survey (Ref. 18) carried out during 1974 found high apparent resistivities associated with the heat flow anomaly. In contrast, relatively low values of electrical resistivities are usually associated with geothermal areas (see Ref. 6 for example).

C. Seismic Ground Noise

High levels of ambient background noise are associated with some geothermal areas (Refs. 19 and 20). Such a survey of the Marysville area had negative results with the lowest values of ground noise associated with the highest heat flow.

D. Microearthquake Survey

Microearthquakes, earthquakes so small that they are not usually detected on the permanent seismic networks, may be causally associated with geothermal areas (Ref. 21). A microearthquake survey of the general area (Ref. 22) indicates activity along a fault or faults extending from northwest of Helena to the southeastern margin of the geothermal area. However, no microearthquakes were located in the geothermal anomaly itself. The fault mechanisms determined include both normal and strike slip motion, but with a consistent northeast-southwest orientation of tension axes.

E. Infrared Survey

An airborne infrared survey was conducted (Ref. 23) in order to test the ability of this technique to detect the geothermal anomaly. The estimated anomaly amplitude required for detection was between 20-100 $\mu\text{cal}/\text{cm}^2\text{-s}$ and, indeed, the geothermal anomaly was not detected. Data processing is continuing, however, with a goal of reducing the noise level of the observations by careful corrections.

F. Gravity Survey

A gravity survey of the geothermal area has been in progress for three years. The relatively rugged topography and lack of elevation control have made gravity work difficult. The results of the survey to date are shown in Fig. 3. The data contoured are terrain-corrected Bouguer gravity values from which the regional gravity values (fitted by a cylindrical surface with values decreasing to the west) have been removed. The gravity effect of the Marysville stock has also been removed from the data utilizing the shape determined from interpretation of the magnetic data. A negative residual gravity anomaly is associated with the geothermal anomaly, but the lowest values of gravity (up to -12 mgal from the regional) are south of the geothermal anomaly.

G. Heat Flow Survey

Before the present study began 15 heat flow values, in four different geographic areas, were available (Ref. 2). During the course of this study 17 holes have been drilled. The depth of these holes has ranged from 50 to 130 m with an average depth of about 100 m. The published data plus the results from 11 of the holes drilled for the project are shown in Fig. 3. The thermal conductivity of the rocks does not vary greatly from locality to locality, so the geothermal gradients, shown in Fig. 3 beside each hole or group of holes, can be compared directly. The values shown have been corrected for topography, and the regional geothermal gradient of about 30°C/km has been removed. Heat flow values in holes drilled during 1974 (not plotted) require the geothermal anomaly be bounded in the southern direction as indicated by the model shape in Figs. 2 and 3.

V. DISCUSSION

A. Models

The preliminary results of the geological and geophysical studies are summarized in Fig. 2. The subsurface shape of the Marysville stock is based on interpretation of the magnetic data, the shape of the heat source body is based on interpretations of the heat flow data, and the contact metamorphic zones are based on petrographic and x-ray analysis. The Marysville stock extends about 2 km southwest and northwest of its surface exposure, while its contacts on the northeast and southeast are steep and nearly coincident with surface exposures. A large vertical dike extends upward from the body near its center and might have been a feeder for volcanics above the stock. The contact metamorphic data indicate that extensive portions of the geothermal anomaly are underlain at shallow depth (less than 300 m) by Cenozoic intrusive rocks.

The resistivity study indicates that the rocks to depths of hundreds of meters have relatively high resistivities and thus low porosity. The seismic ground noise in the area is extremely low, but microearthquake activity is located immediately to the southwest of the geothermal anomaly. A negative residual gravity anomaly is associated with and south of the geothermal anomaly. The gravity anomaly has values up to -12 mgal relative to the regional values.

B. Deep Drilling

A deep exploration drill hole was drilled to a depth of 2.4 km during 1974 at the site indicated on Fig. 1. The geologic section encountered in the drill hole consisted of argillite to a depth of 297 m (Empire and possibly Spokane Formations) and the Empire stock below 297 m. The rocks of the Empire stock increased in grain size with depth, and the rock could be called at different depths a quartz-feldspar porphyry, quartz monzonite, and monzonite. Below a depth of 500 m, several discrete sets of fracture zones with extensive fluid movement were encountered. Final logging and analysis have yet to be completed, but preliminary interpretation of the results imply that the source of the high heat flow values, in the northern part of the geothermal area at least, is hydrothermal fluid circulating through the Empire stock. In this hole, the maximum temperature of approximately 95°C was reached at a depth of about

500 m. From 500 m to total depth, the temperature remained essentially constant. The preliminary geochemical temperatures based on the silica and Na-Ca-K geothermometers (Refs. 24 and 25) are about 115 and 170°C, respectively.

C. Conclusions

On the basis of the information available at the present time, preliminary conclusion is that the immediate source of the geothermal anomaly is a hot water circulating in the Empire stock. Thus, the coincidence of the negative gravity anomaly with the geothermal anomaly appears to be a secondary one in that the negative gravity anomaly is due to the presence of the Empire stock and the heat flow is due to geothermal fluids using the Empire stock as a conduit to shallower depths. It is rather unusual that in this case one granitic stock acts as a reservoir while a second granitic stock, the Marysville, apparently acts as a boundary of the geothermal area. The high resistivity values observed are apparently due to the high resistivity of the Empire stock (except in localized fracture zones in which the geothermal fluids are circulating). The Empire stock must have very low magnetic susceptibility to explain the lack of a significant magnetic anomaly. The end of a zone of microearthquake activity in the immediate vicinity of the geothermal anomaly remains puzzling, as does the significance of the maximum gravity values south of the area of the geothermal area. The highest negative values of gravity, therefore, might either be caused by a deep (3 km or more) source of heat or by a deeply buried southern extension of the Empire stock.

The source of the high-temperature water circulating through the Empire stock remains an enigma and neither of two hypotheses originally suggested as a source of heat in the area can be ruled out, i. e., deep circulation of fluids along a formation or horizon (such as a thrust fault) or interaction of fluids with a deep seated magma chamber (Ref. 2). However, if the source is a magma chamber, then it is deeper than the direct conductive model would suggest because the heat near the surface is being transferred by hydrothermal convection. These results are useful as a test case of a geothermal area in which there are conflicting indications from geophysical studies. These results reiterate the fact that basement rocks can act as reservoirs and that drilling in basement rocks is certainly not precluded for the development of presently economic geothermal resources. The results further indicate that the likelihood of finding shallow (>3 km) magma chambers cooling by conduction alone is probably small and that the direct cause of most geothermal anomalies is convecting ground water. Whether or not in general this convection of ground water is driven by heat from magma chambers will probably have to be proved by indirect evidence in most cases. The implications of these results for the exploration for dry hot rocks are that even in basement rocks, it will be very difficult to distinguish between high gradients due to convection and high gradients due to conduction on the basis of surface geophysical exploration.

ACKNOWLEDGMENT

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Table 1. Major igneous units in the Marysville, Montana area

Locality	Rock type	Age
Upper Part of Empire Shale	Microdiorite sills	Precambrian (?)
Marysville	Granodiorite stock	Cretaceous (79 MY)
Bald Butte	Quartz porphyry plug	Eocene (49 MY)
Empire Creek	Quartz feldspar porphyry stock	Oligocene (40 MY)
Southwest of Marysville stock	Quartz porphyry dikes and sills	Oligocene (37 MY)
Hope Creek	Rhyolite flows	Oligocene (37 MY)
Geothermal Anomaly	Heat source (?)	Quaternary or recent

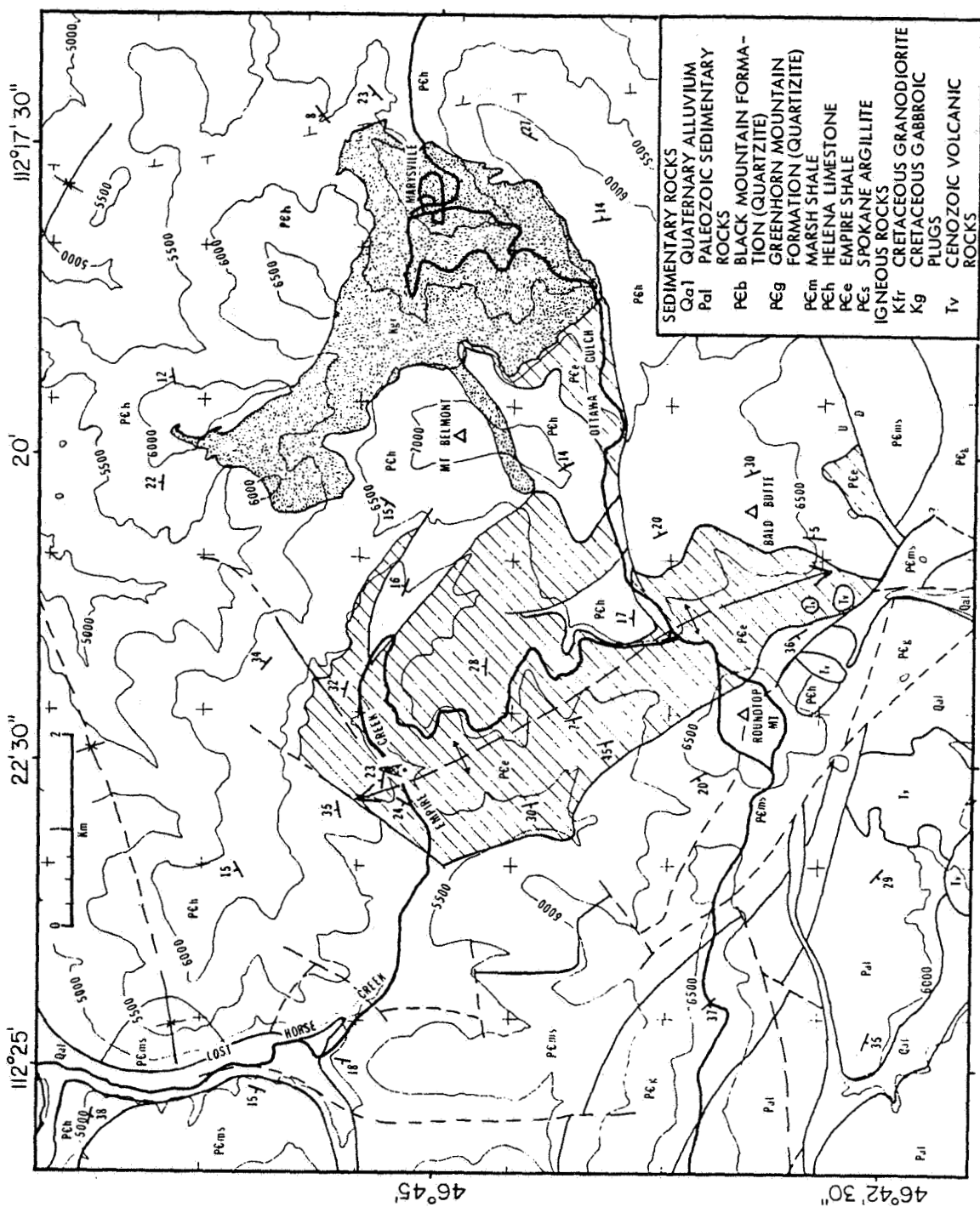


Fig. 1. Topography and geologic map of Marysville geothermal area: contour interval = 500 ft (152 m); location of deep drill hole indicated by derrick symbol; many Cenozoic dikes and sills omitted from map

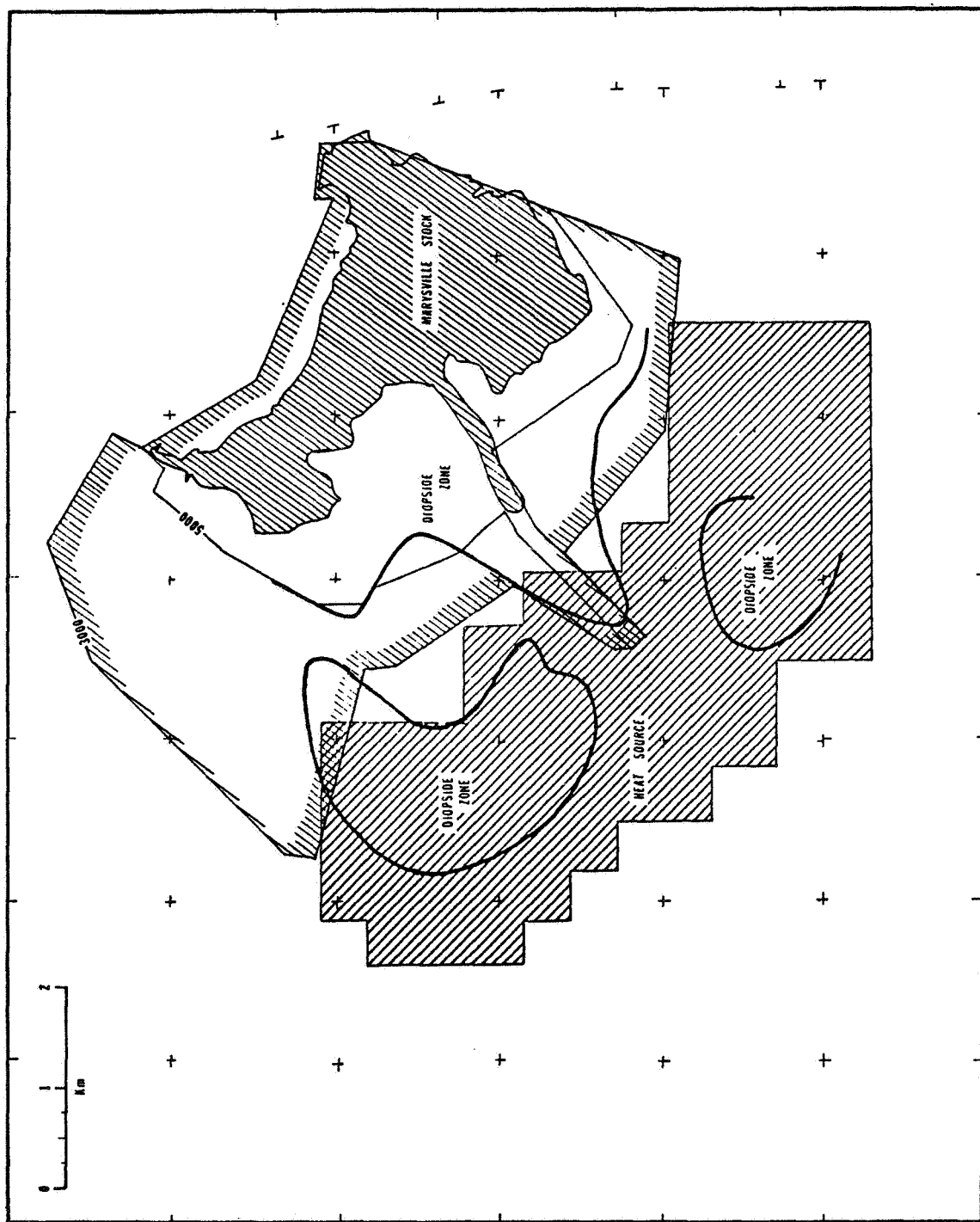


Fig. 2. Contact Metamorphism (heavy lines) and geophysical models of Marysville stock and heat source: contours of Marysville stock in feet above sea level

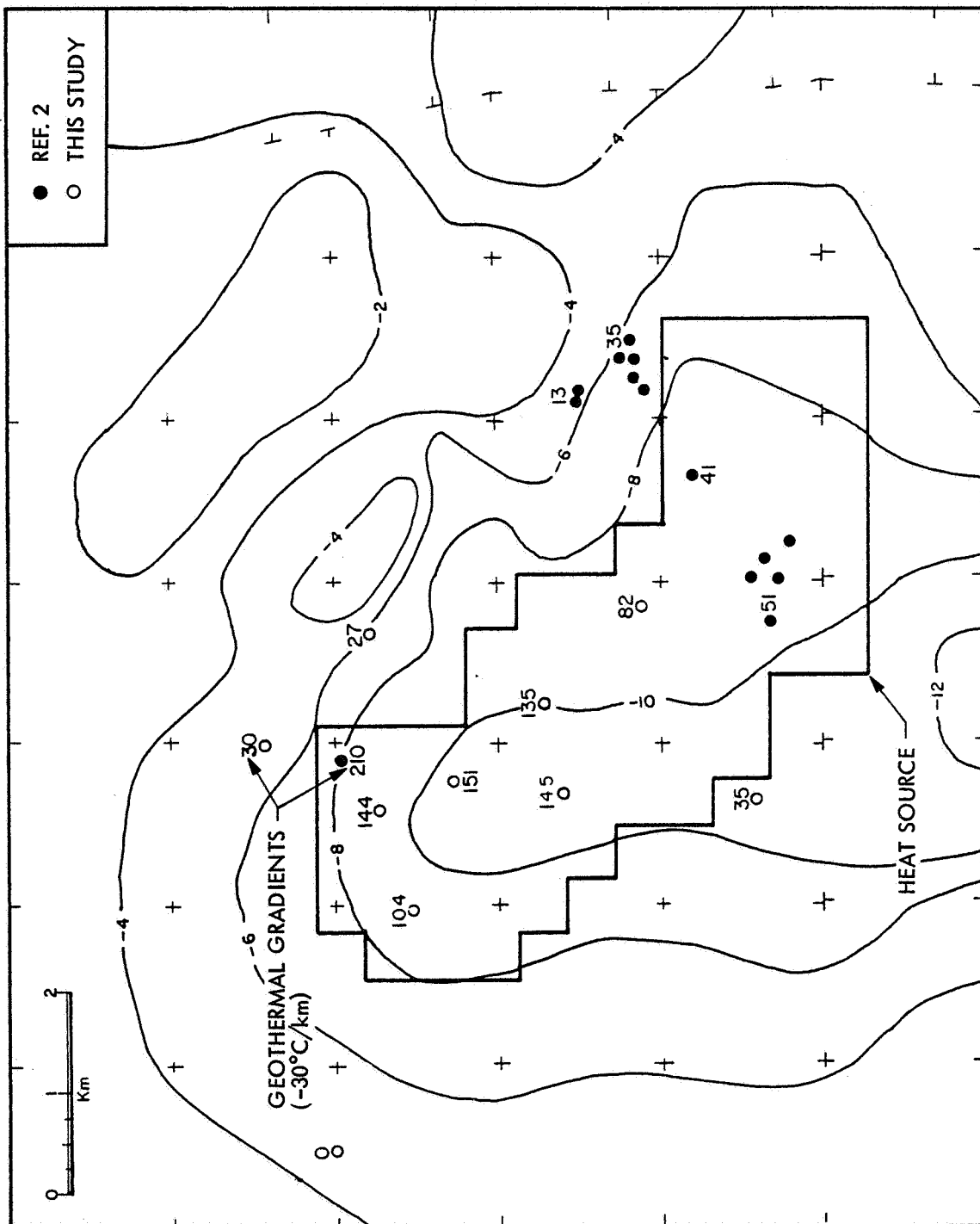


Fig. 3. Heat flow and gravity, Marysville geothermal area: contours of gravity in mgal relative to regional values

ROLE OF THE U.S. GEOLOGICAL SURVEY IN ASSESSING THE NATION'S GEOTHERMAL ENERGY RESOURCES

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The U.S. Geological Survey was established by the Congress in 1879 to evaluate the natural resources of the nation, to conduct the necessary research related thereto, and to classify the public lands. All three of these responsibilities encompass the area of geothermal energy and essentially define the Survey's geothermal program today.

Assessment of the nation's geothermal resources by the Survey is being conducted at a variety of scales and for resources of a variety of grades and types. Geological, geophysical, geochemical, and hydrological investigations all play a role in the evaluation. Although the commodity sought is heat, the regional exploration and evaluation programs are based not only on direct measurements of heat flow, but also on measurements and observations of indirect, but related, phenomena such as post-Miocene silicic volcanic rocks, hot spring waters, hydrothermal rock alteration, subsurface zones of high electrical conductivity, and areas of high microearthquake activity.

Large-scale reconnaissance studies are under way in Oregon, Nevada, Alaska, Idaho, and the region bordering the Colorado Plateau in the Four Corners States. Studies of specific geothermal areas include: the Long Valley, Clear Lake, and Coso Mountains areas, California; San Francisco Mountains, Arizona; Raft River and Weiser areas, Idaho; Upper Arkansas Valley, Colorado; and Yellowstone National Park.

TERRESTRIAL HEAT FLOW STUDIES ASSOCIATED WITH THE
RIO GRANDE RIFT AND NEIGHBORING GEOLOGIC PROVINCES

Marshall Reiter, C. L. Edwards, Charles Shearer, and Charles Weidman
New Mexico Institute of Mining and Technology
Socorro, New Mexico

The Terrestrial Heat Flow Group at New Mexico Institute of Mining and Technology is involved in a detailed heat flow measurement program in the southwestern United States, the work being concentrated along the Rio Grande rift and in neighboring geologic provinces. Over 200 drill tests have been thermally logged, most of these in New Mexico. A high heat flow ribbon is associated with the Rio Grande rift throughout southern Colorado and New Mexico. Additional areas of anomalously high terrestrial heat flow are present to the east and to the west of the Rio Grande graben. Complicated heat flow patterns appear within the Colorado Plateau, suggesting that the Plateau should not be characterized as a uniformly low geothermal province. In New Mexico a geothermal transition between the Colorado Plateau and the Basin and Range province may be inferred from the heat flow data.

SESSION III

ENVIRONMENTAL, LEGAL, AND INSTITUTIONAL RESEARCH

SESSION III. ENVIRONMENTAL, LEGAL,
AND INSTITUTIONAL RESEARCH

SESSION CHAIRMAN: D. N. Anderson

HAWAII GEOTHERMAL PROJECT - R. M. Kamins

LEASING OF FEDERAL GEOTHERMAL RESOURCES -
R. T. Stone

MEASURING GROUND MOVEMENT IN GEOTHERMAL AREAS
OF IMPERIAL VALLEY, CALIFORNIA - B. E. Lofgren

INSTITUTIONAL AND ENVIRONMENTAL PROBLEMS IN
GEOTHERMAL RESOURCE DEVELOPMENT - F. Maslan,
T. J. Gordon, and L. Deitch

IMPERIAL VALLEY'S PROPOSAL TO DEVELOP A GUIDE FOR
GEOTHERMAL DEVELOPMENT WITHIN ITS COUNTY -
D. E. Pierson

SELECTED LEGAL ASPECTS OF GEOTHERMAL DEVELOP-
MENT - S. Sato (abstract or paper not supplied)

HAWAII GEOTHERMAL PROJECT

Robert M. Kamins
University of Hawaii
Honolulu, Hawaii

Hawaii's Geothermal Project is investigating the occurrence of geothermal resources in the archipelago, initially on the Island of Hawaii. The state's interest in geothermal development is keen, since it is almost totally dependent on imported oil for energy.

Geothermal development in Hawaii may require greater participation by the public sector than has been true in California. The initial exploration has been financed by the national, state, and county governments. Maximization of net benefits may call for multiple use of geothermal resources; e. g., the extraction of by-products and the application of treated effluents to agricultural and aquacultural uses.

A guiding role for the Hawaii Government is made the more likely by the 1974 statute which defined geothermal resources as "mineral," and so reserved ownership to the state. Under that law, the Department of Land and Natural Resources has immediate responsibility for fostering geothermal development, a task in which other public agencies necessarily will be involved if Hawaii strikes it rich in geothermal fields.

The State of Hawaii is totally dependent for energy on sea-borne petroleum. Hawaii has no known fossil fuel reserves; there is no coal coming into the State by rail; no natural gas by pipeline; and no regional electric grid to interconnect its electrical systems with those of other states or even with its separate islands. This complete lack of flexibility makes Hawaii particularly vulnerable to dislocations in the global energy market resulting from real or imagined shortages of petroleum.

This is most ironic, since the State is generously endowed with a variety and abundance of natural energy resources: geothermal, solar radiation, ocean temperature differential, wind, waves, and ocean currents — all potential non-polluting power sources. The candidate from among these natural energy sources which shows the highest promise for early power generation at commercial levels is geothermal energy.

The Hawaii Geothermal Project (HGP) was organized to focus the resources of the University, the State, and the County of Hawaii on the identification, generation, and utilization of geothermal energy on the Big Island of

Hawaii. Figure 1 shows the five volcanoes that form this largest island in the Hawaiian chain. Hawaii is also the youngest of the islands and is still experiencing growth from recent activity of the Mauna Loa and Kilauea volcanoes. Consequently, the Big Island was selected as the obvious site for initial geothermal exploration, but subsequent surveys will proceed up the island chain.

Whether a conventional geothermal resource exists — such as the vapor-dominated systems at Larderello, or at The Geysers, or a water-dominated system, as encountered in New Zealand — is subject to speculation. It is certain that enormous amounts of geothermal energy are present in the form of molten magma at 1200°C and in the adjacent hot rock. Ultimately, the HGP intends to look into conversion systems for utilizing this energy of the molten magma directly, but first efforts will be made to identify and develop a conventional geothermal resource.

Phase I of the Project was organized into three separate programs, encompassing the following research tasks:

Geophysical Program — Augustine S. Furumoto

- Photogeologic (Infrared Scanning) Survey
- Electromagnetic Survey
- Electrical Resistivity Survey
- Microearthquake and Microseismic Surveys
- Geochemical Survey
- Thermal Survey of Wells

Engineering Program — Paul C. Yuen

- Reservoir Modeling
- Well Test Analysis
- Ghyben-Herzberg Lens Analysis
- Energy Extraction From High Temperature Brine

Environmental-Socioeconomic Program — Robert M. Kamins

- Regulatory and Legal Aspects
- Land Use and Planning
- Economic Analysis
- Environmental Baseline Studies

The major emphasis of Phase I has been on the Geophysical Program, since the issue of if and where geothermal resources exist is crucial to the project. However, parallel studies were initiated in all supporting programs, so that some progress has been made in identifying and clarifying the technological, environmental, legal, regulatory, social, and economic problems that could obstruct the development of geothermal power in Hawaii.

Although the completion of surveys and interpretation of field data will continue through 1974, it has become obvious — both on the basis of preliminary results from Phase I and from complementary studies conducted on the Big Island over the past several decades — that an exploratory drilling program is essential to establish identity of the subsurface conditions predicated by the surveys.

Figure 2 is an organizational chart for Phase II of the HGP. In addition to continuing the three research programs from Phase I, an exploratory drilling program will be initiated under Dr. Agatin T. Abbott. Overall coordination and management is provided by Dean John W. Shupe. To assure that the Project has both local and national relevance and visibility, a 16-member Hawaii Advisory Committee and a 9-man National Liaison Board were appointed.

The HGP came into being when the 1972 Hawaii State Legislature allocated \$200,000 for geothermal research — \$100,000 to be administered through the County of Hawaii budget. This action was taken prior to the energy crisis and was a farsighted step for a state governing body to take. Additionally, a major source of funding for this Project has been the National Science Foundation. Total support for the HGP through December 31, 1974 is as follows:

National Science Foundation	\$ 252,000	Year 1
(Research Applied to National Needs)	335,000	Year 2
State of Hawaii	100,000	Year 1
(appropriated)	500,000	Year 3
County of Hawaii	100,000	Year 1
Other Public and Private Funds	<u>39,000</u>	
	\$1,326,000	

Except for the \$500,000 appropriated by the 1974 State Legislature for exploratory geothermal drilling — contingent on additional federal matching funds for a research drilling program — essentially all of the above funds will be expended by the end of this calendar year on completing Phase I of the project. Referring again to Figure 1, tentative plans for Phase II call for initial drilling in the Puna Area along the Eastern Rift of Kilauea. A proposal has been submitted to NSF to assist with the drilling program, to get under way in early 1975.

With this overall picture of the Hawaii Geothermal Project in your mind I want to address a basic problem we are studying in the socioeconomic portion of the Project — how to establish rationally the level of investment in geothermal development appropriate to a limited area within the U.S. Most discussions of the economic rationality of energy development until now have been in national terms. How does it look at the state level? What factors are relevant to the calculation of optimal investment and how are they related to state policy?

Most of the factors which I will discuss derive in one way or another from uncertainty — that inability to ascribe probability values for success in action — which is such a key consideration in geothermal resource development anywhere in the world. The resource is so idiosyncratic in its occurrence that even in KGRA's, indeed, even within established productive fields, it is chancy that a well drilled at any given location will hit a useable geothermal supply -- and if it does, how productive the flow will be or how long it will last. Calculating the odds under such conditions is a major task for every management group concerned with investment in geothermal production in the State of California.

Now if uncertainty presents a problem for investment decisions here, among the best-proven geothermal fields of the nation, consider what a problem it is in Hawaii, where there are many good reasons for expecting that the resource exists, but where no production wells have yet been drilled. Given the inherent uncertainties, it is easy to understand why private industry has not yet been willing to invest much to find out if the resource exists in commercially exploitable conditions. There are much less risky investment opportunities here on the mainland.

However, despite the uncertainty, the State and County of Hawaii have appropriated scarce public funds to help finance the study and development of this chancy resource. Was this investment decision rational and in the public interest? I won't offer a categorical answer, but will suggest the considerations needed for one.

The primary consideration is that a geographically isolated state such as Hawaii faces conditions of uncertainty that in social context dwarf those pertaining to geothermal discovery. Consider what I have already said about Hawaii's small dot in the national energy picture. It is almost completely dependent on imported petroleum to light every room, cook every meal, and turn every motor in the state. The recent fuel shortage drove home the point that an oil embargo, shipping tieup or any other prolonged stoppage of the oil flow would quickly cripple the economy of the state. This kind of uncertainty is difficult to live with in a power-dependent society, and so the development of an indigenous power source becomes extremely valuable to the state as a kind of energy insurance.

Not only is the Hawaii government concerned with safeguarding the energy supply to maintain the local economy, it is also increasingly concerned with economic growth to provide more jobs. Unemployment is a problem in many parts of the U.S.; in Hawaii it is a bad problem, running over 8% — which is well above the national average — and still rising. Public welfare applications in Hawaii have doubled over the past 12 months and are also rising. Under these circumstances, a new energy source that provides a base for growth and jobs may have a social value far exceeding the profits which may be realized by firms engaged in producing and using geothermal power.

It is important to Hawaii that expansion of the energy supply be low in pollutants. The land mass is so small that geography as well as economics dictates that most generating plants be near residential or resort areas. It would be costly in many ways for Hawaii to accept high-sulfur oil or other polluting fuels, as is proposed to help the nation in the energy bind.

Another consideration in Hawaii's energy development policy is inflation. The brutal rate of price increases which Hawaii is experiencing, along with the rest of the nation, gives additional incentive to find indigenous energy sources which may be cheaper, as well as cleaner, than fossil fuel. Electricity rates and gasoline prices in Hawaii are among the very highest in the U.S., and they contribute to an overall cost of living that is second only to Alaska's. The development of geothermal power could not only bring some relief to family

budgets but could also help overcome the cost disadvantage under which Hawaii suffers in competition with other areas in attracting industries, other than in tourism.

Finally, the development of geothermal power on the Island of Hawaii could help the state government achieve another policy objective — to decentralize the population of the tiny state. Now, more than 80% of the population lives on Oahu (most of them in or near Honolulu), already one of the most densely occupied communities in the nation, with more people crowding in every year to be where the jobs are. Lacking constitutional means of turning away new residents, the state is seeking ways of encouraging them to move to the uncrowded outer islands; however, the economic base (the jobs) has been lacking there. However, if a major energy source were to be developed on the Island of Hawaii, that base could be created on the largest land mass in the archipelago. I might point out that such development could offer public economies as well as esthetic advantage in helping to preserve the last, unsubdivided valleys and open beaches of Oahu. Crowding costs more, the per capita costs of local government are higher in Los Angeles than in Honolulu, and higher in Honolulu than in Hilo. Decentralization should save tax dollars.

There are, then, several social benefits which a state in Hawaii's circumstances could receive from geothermal development: energy insurance, creation of a new economic base and more jobs, anti-inflationary help, environmental protection, and population dispersal. Attaining these benefits may be worth tens or hundreds of millions of dollars annually to overall Hawaiian society, yet worth much less to the private firms that would decide whether or not to invest in geothermal development. In the vocabulary of economics, this may be a case where externalities are of critical importance. There may exist a discrepancy between perceived private benefits and social benefits of a large order, so that when the difference is accounted for, total benefits would equal or exceed the total costs.

If analysis shows that the discrepancy does exist, and that by best judgment it is large, then the state may be justified to act to bring about a scale and pace of geothermal development greater than would result from private enterprises operating in the absence of government stimulation.

A broad cost-benefit analysis of the kind I have just sketched has not yet been made; we are just starting on it for Hawaii. And yet I think that its salient points have been intuitively understood by political leaders in the state for they have appropriated funds to support research and drilling programs for geothermal development, and additional funds for other alternative energy sources. And, if other social investments are indicated in order to stimulate geothermal development, this rationale and understanding may again be appealed to.

For example — returning again to the theme of uncertainty — it is quite possible that geothermal resources will be discovered in a corner of the Island of Hawaii, which in recent times has received lava flows from eruptions of Kilauea. This must be known to Lloyd's of London. The premium rates on insurance to cover a generating plant and other capital investments at a

geothermal field in Puna might be prohibitively high for a private enterprise and yet readily covered by the social benefits reasonably attributable to the development. In that case, it may be good and politically acceptable public policy for the Hawaii government to share some of the inherent uncertainty by subsidizing some or all of the extraordinary insurance that may be necessary for the geothermal developers who undertake the risk of working in an active volcanic area.

The Hawaii government has already acted to reduce a different kind of uncertainty in geothermal development by answering the question as to who owns whatever geothermal resources there may be in the state. Act 241 of the 1974 Legislature asserted that the State of Hawaii owns them, as successor in title to mineral reservations kept by the Kamehamehas when they reigned in the Kingdom and divided the lands more than a century ago. Like any statute, this declaration of ownership is subject to challenge in the courts, but unless it is overturned, parties interested in drilling for geothermal resources in Hawaii will have the certainty that they will deal with the State Department of Land and Natural Resources.

However the question of resource ownership is ultimately settled, it seems likely that in Hawaii's circumstances the government will retain a lively interest and play an active role in geothermal development in the Island State. I have tried to identify the basis of that interest and outline the factors to be considered in arriving at a rational policy for public investment in the potential new energy source. Whether public investment would most effectively be made by direct subsidies, by indirect subsidy through tax incentives, by providing roads and other facilities needed for geothermal field development, by loans or loan guarantees to private companies, or by the state entering into joint enterprises with them — or indeed undertaking geothermal development as a public enterprise — all these alternatives remain to be explored. In our research we are not attempting to determine what the role of government should be in Hawaii's geothermal future, but rather to lay out a rationale which decision-makers and the electorate may find helpful in making that judgment.

We are interacting with several state agencies — Planning and Economic Development, Land and Natural Resources, the Office of the Attorney General — and with the County of Hawaii in conducting our study. The results should have immediate applicability to the 50th State.

However, we also perceive that the public policy considerations we are trying to elucidate will be applicable to other parts of the nation, particularly those states which, like Hawaii, have strong incentives for developing indigenous sources of energy.

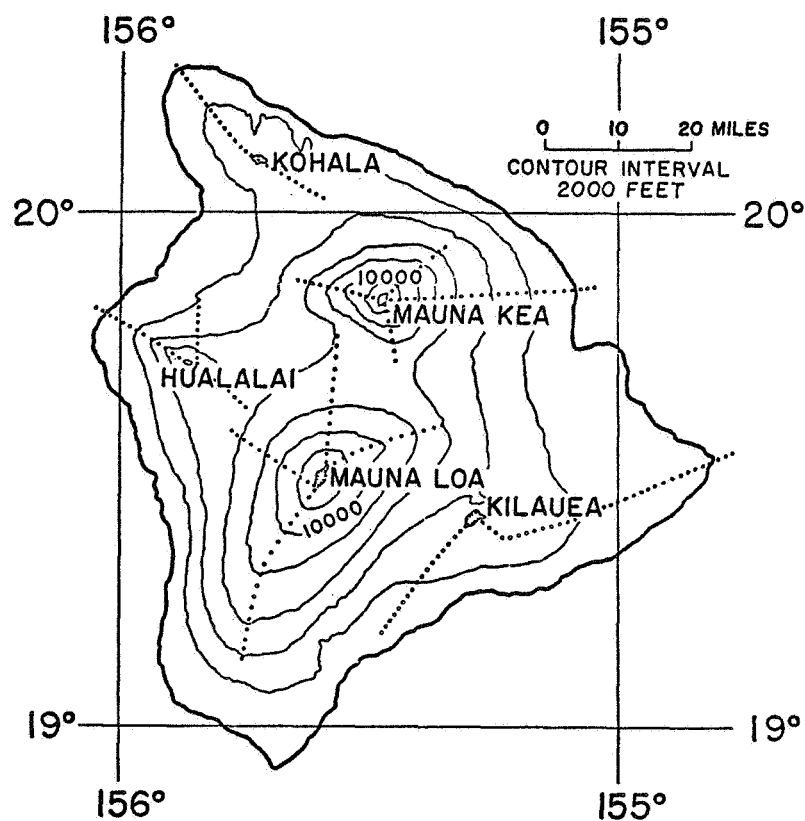


Fig. 1. Volcanoes and rift zones on the island of Hawaii

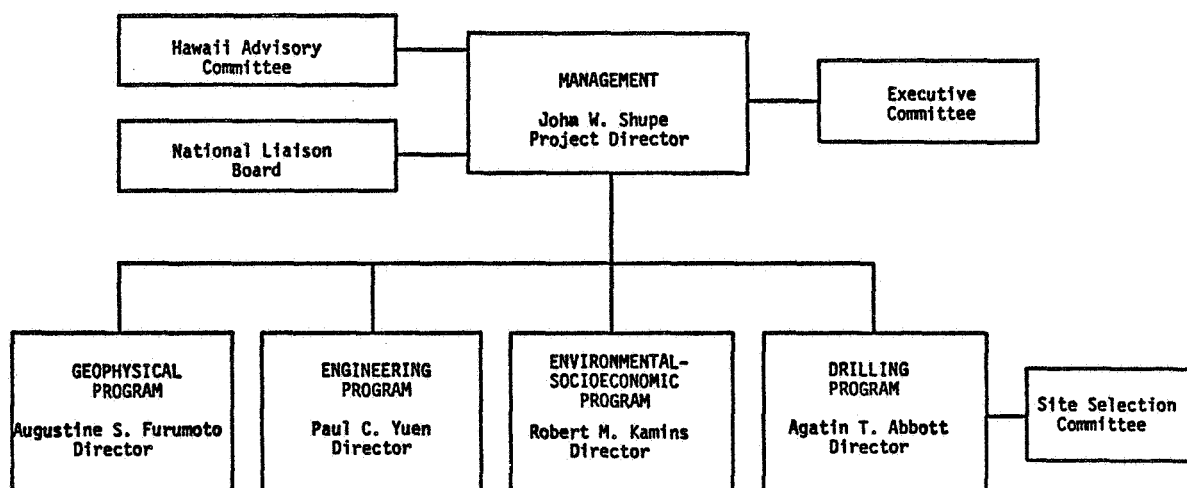


Fig. 2. Hawaii Geothermal Project, Phase II, organization chart

LEASING OF FEDERAL GEOTHERMAL RESOURCES

Reid T. Stone
U.S. Geological Survey
Menlo Park, California

Pursuant to the Geothermal Steam Act of 1970 and the regulations published on December 21, 1973, the first Federal geothermal competitive lease sale was held on January 22, 1974, by the Department of the Interior, offering 33 tracts totalling over 50,000 acres in three Known Geothermal Resource Areas in California. On January 1, 1974, Federal lands outside Known Geothermal Resource Areas were opened to noncompetitive lease applications, of which, 3,763 had been received by June 1, 1974. During fiscal year 1974, a total of 22 competitive leases had been issued in California and Oregon. The principal components in the Department involved in the leasing program are the Geological Survey and the Bureau of Land Management. The former has jurisdiction over drilling and production operations and other activities in the immediate area of operations. The latter receives applications and issues leases and is responsible for managing leased lands under its jurisdiction outside the area of operations. The interrelationships of the above agencies and the procedures in the leasing program are discussed.

I. INTRODUCTION

On December 24, 1970, the Geothermal Steam Act (Public Law 91-581) was signed into law. This act authorized the Secretary of the Interior to lease certain public lands for development of geothermal steam and associated geothermal resources. At once, an interdisciplinary Geothermal Task Force was established within the Department. The Task Force was assigned responsibility for preparing leasing and operations and unit regulations for the proposed geothermal resources leasing program and for preparing environmental impact statements required under the National Environmental Policy Act of 1969. To assure the widest possible public participation and input, proposed regulations were published three times in the Federal Register. Finally, after careful consideration and revision, the regulations were officially promulgated on December 21, 1973.

The final environmental impact statement published on October 23, 1973, provided the public with additional information about the program and furnished additional basis for the preparation of leasing regulations.

In addition, on February 6, 1974, the Secretary of the Interior established, by Secretarial Order 2962, a Geothermal Environmental Advisory Panel to

advise the Supervisors of the Geological Survey (GS) and the Authorized Officers of the Bureau of Land Management (BLM) and other land managing agencies in carrying out their responsibilities related to environmental impacts in connection with operations under leases issued under the Geothermal Steam Act of 1970.

These, in brief, were the actions preceding or directly related to announcement of the geothermal leasing program. Before moving to a discussion of the mechanics by which the Department administers the leasing program, I should like to differentiate between the two types of leases - competitive and noncompetitive.

According to law and regulation, public land classified by the U.S. Geological Survey as Known Geothermal Resources Areas (KGRAs) can be leased only competitively to the highest qualified bidder. All other public lands open to geothermal leasing, including those classified as prospectively valuable for geothermal resources, are subject to noncompetitive lease applications. In determining whether lands should be classified as KGRAs the Geological Survey considers geology, nearby discoveries, and competitive interest. Under the regulations, an overlap of 50% or more in noncompetitive lease applications is considered evidence of competitive interest and subjects the land involved to classification as a KGRA.

On December 21, 1973, the Secretary of the Interior announced the first competitive lease sales on three KGRAs in California for January 22, 1974. It was also announced that applications for noncompetitive leases for Federal lands outside KGRAs would be accepted beginning January 1, 1974. Before bringing you up to date on current results of the leasing program, in terms of the applications received and the leases issued, I will first discuss some of the more important aspects considered and some of the interrelationships involved in the administration of the program.

Two components of the Department of the Interior primarily involved in the geothermal leasing program are the Bureau of Land Management and the U.S. Geological Survey. The former is responsible for 1) receiving lease applications and issuing leases noncompetitively, 2) holding competitive lease sales and issuing ensuing leases, and 3) managing leased lands under BLM jurisdiction outside the immediate area of geothermal operations. When lands are under other Federal jurisdiction (generally U.S. Forest Service), that agency manages leased lands outside the immediate area of operations. Under the regulations the BLM responsible official, or other management agency responsible official, is known as the "Authorized Officer."

The Geological Survey responsible official is known as the "Supervisor." This official, as a representative of the Secretary and subject to the direction and authority of the Director of the Geological Survey and other appropriate Geological Survey officials, has jurisdiction over 1) drilling and production operations, 2) handling and measurement of production, 3) determination and collection of royalties and, 4) in general, all operations conducted on a geothermal lease subject to the regulations in 30 CFR 270 and 271 and the applicable regulations in 43 CFR Group 3200.

The Supervisor, in performing his duties, shall ensure that all activities within the area of operations will conform to the best practices, are conducted in such a manner as to protect the deposits of the leased lands, and will result in the maximum ultimate recovery of geothermal resources, with minimum waste. He shall also ensure that such operations are consistent with the best use of the land and the protection of the environment. The regulations require that the Supervisor shall, prior to approval of a plan of operations or prior to issuing orders or rules, consult with and receive comments from appropriate Federal and State agencies, lessees, operators, or interested parties. For example, any plan of operation must be approved by the appropriate land management agency.

I previously mentioned the Geothermal Environmental Advisory Panel established by Secretarial Order 2962 to advise Supervisors and Authorized Officers. Briefly, the panel is responsible for giving advice on environmental aspects in any new geological or geographical areas. The panel is also available on request for additional advice or consultation regarding operations which may affect the environment under any geothermal lease. The Supervisor (for plans within the area of operations) and the Authorized Officer (for plans or permits outside the area of operations) shall, prior to his approval of such plans, submit the plans in any new geological or geographical areas to the Chairman of the Panel. The Chairman of the Panel, within 15 days, shall respond as to whether the panel intends to provide advice in that particular case. The panel will have 30 days after receipt of the plan within which to supply its advice, unless the time is extended by the Secretary.

Now, for some specific examples of the interrelationship between the Geological Survey and BLM, the U. S. Forest Service, or other land management agencies.

II. COMPETITIVE LEASE SALES

When BLM, on its own motion or in response to nominations from industry, proposes to offer lands for leasing within KGRAs, the Geological Survey is responsible for determining the appropriate parcelling of tracts and for establishing rentals and royalties. The GS will report to BLM on needed lease terms and conditions, including environmental and surface rehabilitation stipulations, relating to mineral exploration and extraction. The GS makes all geologic, engineering, and economic value determinations including a resource evaluation on each tract to be offered and a postsale recommendation to BLM regarding acceptance or rejection of the high bonus bids. The GS makes geologic and engineering inputs to environmental analyses and environmental impact statements prepared by BLM in advance of competitive lease sales. At that time, GS and BLM usually consult and confer regarding any special lease stipulations needed for operational requirements or environmental protection measures. The Forest Service and GS consult in the same way on environmental analyses and lease stipulations on areas proposed for leasing in National Forests.

III. NONCOMPETITIVE LEASE APPLICATIONS AND ISSUANCE

The first of each month becomes a new filing period for noncompetitive lease applications. These lease applications, filed with BLM state offices, are opened at the end of each month and serial register pages are made. Copies of the serial register pages are sent to the BLM Authorized Officer and the Geological Survey for their information. After further processing and determination of adequacy of application, if the lands covered by the application are determined to be subject to leasing, the application will be sent to GS for a KGRA report and recommended lease stipulations and to the BLM or another land management agency Authorized Officer for review, determination of whether or not an environmental analysis is required, and any other recommendations. If the lands are not determined to be in a KGRA and if the environmental analysis indicates that issuance of a lease will not cause a major environmental impact or constitute a major Federal action, GS and BLM, or other land management agencies, develop any necessary special lease stipulations. Then, if these are accepted by the applicant, the lease will normally be issued.

IV. PLAN OF OPERATIONS

The lessee must submit a plan of operation pursuant to regulation prior to entry upon the leased lands for any purpose other than casual use. Operations will not be permitted on the lands until the plan of operation has been approved. The contents of the plan of operations are outlined in 30 CFR 270.34. The plan is submitted to the Supervisor and both the Supervisor and the Authorized Officer of the appropriate land management agency must approve the plan.

The Supervisor, after receipt of the plan of operations, sends a copy to the appropriate Authorized Officer and arranges for discussions of the plan, inspection of the area when appropriate, consideration of necessary modification of the plan, and review by the Authorized Officer of any GS environmental analysis for the proposed operations. Following completion of the environmental analysis and agreement on the plan, the plan of operations is formally approved by the Supervisor and the Authorized Officer. The copy of the approved plan, from the Supervisor to the lessee, specifies the notices and permits required by the Supervisor in the area of operations and those required by the Authorized Officer in the remainder of the leased area. Also, in any new area the plan of operation is furnished to the chairman of the Geothermal Environmental Advisory Panel for consideration and possible suggestions regarding the environment.

V. GEOTHERMAL RESOURCE EXPLORATION OPERATIONS

Exploration operations for unleased public lands administered by BLM are covered in 43 CFR 3209; permits are obtained from the Authorized Officer. Exploration operations on leased lands are covered in 30 CFR 270.78. These permits are obtained from the Supervisor.

The BLM furnishes GS with a copy of the Notice of Intent for exploration operations on unleased lands for review of any engineering or geologic hazards and a copy of their recommendations for appropriate conditions of approval. For example, in some areas the allowed depth of seismic or shallow temperature holes may need to be restricted so that unwanted hot springs or geysers are not created. The GS, likewise, furnishes BLM with copies of the Notice of Intent for exploration on leased lands, and receives suggestions on appropriate conditions of approval regarding the protection of surface resources and uses.

VI. GEOTHERMAL RESOURCES OPERATIONAL ORDERS

The Supervisor, as part of his responsibility in administering the operating regulations, issues "Geothermal Resources Operational (GRO) Orders." These are formal, numbered orders implementing, in more detail, the manner in which 30 CFR 270 will be complied with in an area, region, or any significant portion thereof. Most of the GRO orders the Supervisor issues are applicable in all the states where geothermal operations are conducted.

One of the most important orders, from an operational standpoint, will be on drilling procedures. This will cover well casing and cementing, pressure testing, blowout prevention equipment and tests, mud program, and well logging requirements. There will be an order on the requirements for 1) plugging, suspending, or abandonment of wells, 2) well completion procedures and required wellhead equipment, 3) air quality requirements, noise suppression, water quality protection, and other antipollution and environmental protection factors, and 4) various forms, reports and records required by the regulations. Any requirements of GRO orders relating to surface uses or resources will be coordinated with the appropriate land management agencies. Other operational requirements will be coordinated, as appropriate, with other agencies such as the California Department of Oil and Gas, with industry, and with the public.

The preceding has been a general overview of the way we have begun to operate the geothermal resources leasing program. Please understand that this is an evolving program. As more experience is acquired, some changes in the way we conduct the program may be expected.

Earlier I stated that I would bring you up to date on leasing activity thus far. First, on the first competitive lease sale in three KGRAs in California, 33 tracts of land totalling 52,788 acres were offered. Total high bids were \$6.8 million dollars on 23,598 acres bid on. A total of 21 leases have been issued. In addition to this first sale, one lease has been issued as the result of a competitive sale on a KGRA in Oregon, held in fiscal year 1974. Since the beginning of fiscal year 1975, a third sale has been held on a KGRA in Utah. Twelve leases covering 23,391 acres are in the process of being issued. Regarding the future of competitive sales, the Department is considering about 25 KGRAs for possible lease sales in fiscal year 1975. It is proposed that about 15 sales will actually be held, depending upon personnel and fiscal limitations.

With regard to noncompetitive applications, 3,763 applications had been received by June 1, 1974, covering about 8 million acres of public land. No leases have as yet been issued. It is estimated that a total of 6,500 applications will be filed between January 1, 1974 and June 30, 1975, including the 3,763 previously mentioned. It is also estimated that about 20%, or 1,300, of these applications will contain sufficient overlap to require rejection and reclassification of the areas concerned as KGRAs. It is hoped that approximately 1,000 leases will be issued during fiscal year 1975 as a result of noncompetitive applications, in addition to leases issued as a result of competitive lease sales.

In addition to the above, investigations to determine resource values will be undertaken because of the scarcity of background data on geothermal resources development. This will be coordinated with geologic research activity to obtain the best possible information with which to establish lease sales.

In closing, our objectives in the geothermal resources leasing program are as follows:

- (1) To assure conservation of the geothermal resource, including maximum ultimate recovery of the resource and prevention of waste, both below the ground and in utilization after production.
- (2) To promote safety of operations from the public health and safety down to the individuals and equipment involved in the actual geothermal operations.
- (3) To protect the environment by assuring that mineral exploration and production are conducted with the maximum protection of the environment including rehabilitation of disturbed lands.
- (4) To assure that maximum coordination is achieved among all Federal agencies involved and that maximum efficiency and economy in our operations results.
- (5) To assure that the Federal Government receives its fair share of the resources.

All of us are engaged in what seems to me to be a most challenging and useful enterprise in developing additional vitally needed energy sources. I fully believe that geothermal energy will play a significant role and I am happy to have an opportunity to work in the Federal leasing program.

MEASURING GROUND MOVEMENT IN GEOTHERMAL AREAS OF IMPERIAL VALLEY, CALIFORNIA

Ben E. Lofgren
U. S. Geological Survey
Sacramento, California

Significant ground movement may accompany the extraction of large quantities of fluids from the subsurface. In Imperial Valley, California, one of the potential hazards of geothermal development is the threat of both subsidence and horizontal movement of the land surface. Regional and local survey nets are being monitored to detect and measure possible ground movement caused by future geothermal developments. Precise measurement of surface and subsurface changes will be required to differentiate man-induced changes from natural processes in this tectonically active region.

I. INTRODUCTION

As with extractions and injections in oil-field and ground-water reservoirs, a direct relationship is expected in hot-water geothermal systems between pressure changes induced in the system and ground deformation that might result (Ref. 1). Experience in many areas of fluid-pressure change indicates that both vertical and horizontal components of deformation may occur as a result of either the compaction of surficial unconsolidated deposits or of deep-seated tectonic readjustments triggered by stress changes. Even subtle changes of stress at depth sometimes cause serious surface movements. Such problems undoubtedly will become more commonplace and severe as man's development of natural resources progresses.

Land subsidence, caused by the withdrawal of water, oil, and gas, has become common in the United States, affecting probably 10,000 mi² (25,900 km²) of intensely developed land in five States (Ref. 2). Maximum subsidence is 29 feet (9 m) in the San Joaquin Valley and Long Beach areas of California, 13 feet (4 m) in the Santa Clara Valley of California, and is in excess of 8 feet (2.4 m) in the outskirts of Houston, Texas (Ref. 3). Horizontal ground movement exceeds 12 feet (3.7 m) in the Wilmington oil field of the Long Beach area, and, although largely unmeasured, it probably continues in numerous heavily pumped ground-water basins of the west. Extensive earth fissures and cracks forming on the margins of numerous heavily pumped basins, principally in Arizona, and presently threatening land use in several areas, are caused by significant horizontal shifting of the ground. These features are attributed by the author to steep hydraulic gradients induced by pumping.

One of the potential hazards of geothermal production in Imperial Valley, either for power generation or for water or mineral supply, is the threat of land subsidence and lateral ground movement that might result. Where large quantities of geothermal water are extracted or steep pressure gradients are induced in the hydrologic system, significant deformation of the land surface may occur. At Wairakei, New Zealand (Ref. 4), in one geothermal field, where large quantities of fluids have been produced, both horizontal and vertical ground movement has been measured. Subsidence affects more than 25 mi² (65 km²), and the maximum subsidence rate is about 1.3 feet (0.4 m) per year. Total subsidence exceeds 10 feet (3 m), and, significantly, the area of maximum subsidence is outside the production field. Similar effects could occur in other "hot-water" geothermal fields. Periodic resurveys of bench marks throughout a production area and the surrounding region are needed to determine not only possible ground movement resulting from geothermal developments but also movement related to other geologic processes.

Imperial Valley is a "flat," arid area that is irrigated and intensively farmed with water from the Colorado River. It occupies part of a deep, sediment-filled structural trough on the border between the continental block of the western United States and the oceanic block of the eastern Pacific. A number of major and minor faults (Ref. 5, Fig. 3), largely masked by the alluvial deposits, traverse the structural trough. Currently this is one of the most tectonically active areas of the country.

Thermal gradients are unusually high throughout much of Imperial Valley; however, eight known areas of anomalously high temperatures appear especially favorable for geothermal production (Fig. 1). Several of these anomalies already have been test-drilled and have active hot-water (which flashes to steam) wells ready for production; others are scheduled for test drilling in the near future. Wherever deep wells have been tested, hot-water geothermal conditions have been observed. This suggests that as geothermal development progresses, not only will large quantities of thermal waters be produced, but also production will have an intimate effect on the hydrologic regime of the overlying ground-water reservoir. The possibilities of land subsidence, lateral deformation, and infringements on existing water rights, therefore, are very real in Imperial Valley.

Figure 1 shows eight of the more prominent geothermal anomalies reported by the U. S. Bureau of Reclamation in 1971 (Ref. 6). Of these, the Buttes anomaly abutting Salton Sea southwest of Niland (Fig. 1) and the Heber anomalies due south of El Centro have received the most attention by industry, and have production wells awaiting pilot-testing. Also, near the center of the East Mesa anomaly 7 miles (11 km) southeast of Holtville, several deep test wells by the Bureau of Reclamation have produced hot water and steam and are presently undergoing further testing.

II. MONITORING PROGRAM

A. Vertical Control

Figure 1 shows the network of leveling established to measure possible vertical changes that might accompany geothermal development in Imperial Valley. The lines of first-order leveling running east, north, and west from El Centro had been surveyed several times prior to 1971, and indicated considerable tectonic movement was occurring in this portion of the structural trough. Tectonism will undoubtedly continue, and may increase, as geothermal production continues.

During the winter of 1971-1972, the first-order lines of Fig. 1 were again leveled by the National Geodetic Survey, and, also, the second-order lines were established and surveyed by other agencies under direction of the National Geodetic Survey. This 1971-1972 reference datum serves as a base from which subsequent elevation changes can be calculated. During the winter of 1973-1974, the first- and second-order networks were again surveyed to verify measurements of the 1971-1972 survey and detect changes that had occurred during the ensuing years. Figure 2 shows, in addition to the approximate location of the principal known faults traversing the region, the amount of vertical change along the first-order lines during the 2-year interval 1971-1972 to 1973-1974. In these computations, the bedrock tie west of El Centro was considered stable, and all other points in the net were considered floating. Interestingly, bench marks near Calexico and at the bedrock tie east of El Centro showed little or no change during this 2-year period. El Centro subsided roughly 0.6 inch (1.5 cm), and a general northward tilt of about 5 inches (13 cm) was measured in the 53 miles (85 km) from south to north in the valley. No explanation for this apparent northward regional tilt is attempted here; however, it is quite apparent that the modest activities in the three geothermal anomalies being tested had little or no effect. Results of the second-order leveling are not available for reporting here. As required by State and County ordinance, bench marks at each geothermal production site will be resurveyed periodically to reference ties of the first- and second-order nets to detect subsidence that may accompany geothermal production. Figure 3 shows the three locations where local level networks are being monitored by developers to determine if changes are occurring in areas of geothermal development.

In order to monitor possible elevation changes occurring on the southern margin of Salton Sea, related to either tectonic readjustments or to geothermal production, two continuous stage recorders were installed at strategic locations to correlate fluctuations of the sea with two other stage gages of long record on the west shore of the sea. One of these new stage recorders is near the southern tip of the sea (Fig. 3), the other within the geothermal anomaly southwest of Niland. Each of the stage gages is being tied into the valleywide network of vertical control. Differential elevation changes of less than a centimeter around the southern margin of the sea should be detectable with these recorders. Interpretation of the first year of correlative records from these recorders is in progress.

B. Horizontal Control

Two types of horizontal control nets are currently being monitored in Imperial Valley: first, a highly precise regional trilateration network spanning the structural trough to measure regional tectonic movement, and, second, local arrays of precise distance measurements in each of the areas of geothermal development to detect possible ground movement accompanying geothermal production.

Figure 4 shows the regional network being monitored by the Geological Survey, using geodolite equipment capable of accuracies of 1 unit in 10^7 units of distance. Late data suggest as much as 0.02 inch (5 mm/year) of right-lateral horizontal tectonic movement is occurring in the Obsidian Buttes area (Fig. 4) southwest of Niland, along what may be an extension of the Brawley fault. Interestingly, this indicated movement is in the general area where a number of recent geothermal test wells have been drilled and tested. The tectonic movement, however, predates the drilling of the wells.

Figure 5 shows the arrays of distance measurements being monitored in the Buttes area southwest of Niland to detect any horizontal movement. These local nets are being resurveyed by the Geological Survey using electronic distance-measuring equipment capable of accuracies of 2 units in 10^6 units of distance. Distance changes of only a few millimeters along these controlled lines can be detected. Because these distance measurements can be made so inexpensively, extra shots have been made in the event they are needed for future reference. Similar arrays are being monitored in the Heber and East Mesa areas; however, in these areas no elevated reference points are available and long line-of-sight controls are more difficult. Control lines extend not only across geothermal areas where geothermal changes are anticipated, but also across structural zones where tectonic movement might occur.

III. SURFACE AND SUBSURFACE INSTRUMENTATION

Consider for a moment a geothermal area in which thermal fluids are extracted at depth at one location, and these and other fluids are injected nearby to minimize formation-pressure declines and subsidence (Fig. 6). Extractions cause a drop in formation pressures, compaction, and subsidence. Injections cause a pressure buildup, expansion, and rebound. These vertical changes, y_1 and y_2 in Fig. 6, are significant in understanding the mechanics of the geothermal system. In addition, steep pressure gradients may develop between the two wells, and possibly horizontal ground movement as represented by the lower arrows in Fig. 6. To monitor possible horizontal movement, precise distance measurements, x_1 and x_2 , x_3 and x_4 in Fig. 6, are needed between the extraction and injection wells. Compression would be greatest near the extracting well, and horizontal tension would tend to develop near the injection well. This type of horizontal movement, with significant compression in the area of fluid-pressure decline and tension around the perimeter, has been observed in numerous stressed subsurface reservoirs.

If the land surface tilts, as shown in Fig. 6, the tilt should be at a maximum somewhere midway between the centers of extraction and the injection, and could be recorded by a tiltmeter at this midpoint. We have reason to believe, however, that in many instances the land surface does not deform as a

stressed beam. Rather, shear seems to develop along near-vertical planes, with individual blocks between the shear planes moving vertically up or down (Fig. 6). We are installing tiltmeters at a few sites to determine what type of surface deformation actually occurs. Also, at several locations where shallow ground water is being pumped in the vicinity of deep geothermal wells (see Fig. 6, right), extensometers are being installed to differentiate deep compaction caused by deep geothermal extractions from relatively shallow compaction due to ground-water production. Without some method of differentiating these two processes, geothermal developments can be unjustly blamed for subsidence caused by ground-water pumping.

At East Mesa, 17 miles (27 km) east of El Centro (Fig. 1), where the U. S. Bureau of Reclamation is experimenting with deep extractions and injections in the geothermal reservoir, tiltmeters and extensometers are being installed on an experimental basis, as shown in Fig. 7. Two sensitive tiltmeters, installed in 10-foot (3-m) pits to minimize thermal problems, are being positioned between the four extraction wells and the one injection well. Also, two mid-depth extensometers are being positioned between the area of geothermal development and nearby farmlands to monitor changes in water levels and compaction in the upper 1150 and 1400 feet (350 and 430 m), respectively, of alluvial deposits. Already in this area, even before significant geothermal developments have begun, numerous complaints from nearby ranchers have charged that geothermal drilling has had adverse effects on their water wells.

IV. CONCLUSIONS

As in three other geothermal resource areas of the west, regional and local networks of vertical and horizontal surveys have been established in Imperial Valley to monitor ground movement that might accompany geothermal developments. Periodic resurveys of these nets will be the basis for calculating vertical and horizontal changes that occur between surveys. Also, recording tiltmeters, extensometers, and stage gages on Salton Sea are being maintained to detect changes as they occur. Various Federal, State, and local agencies are involved in this monitoring program.

Surface changes may be caused by geothermal extractions, fluid injections, induced hydraulic gradients, thermal changes, landslides, and tectonism. To differentiate ground movement caused by geothermal extractions from changes due to other geologic processes is one of the principal challenges of this research project. In most instances, several years of records will be required before geothermal effects can be determined and firm conclusions reached.

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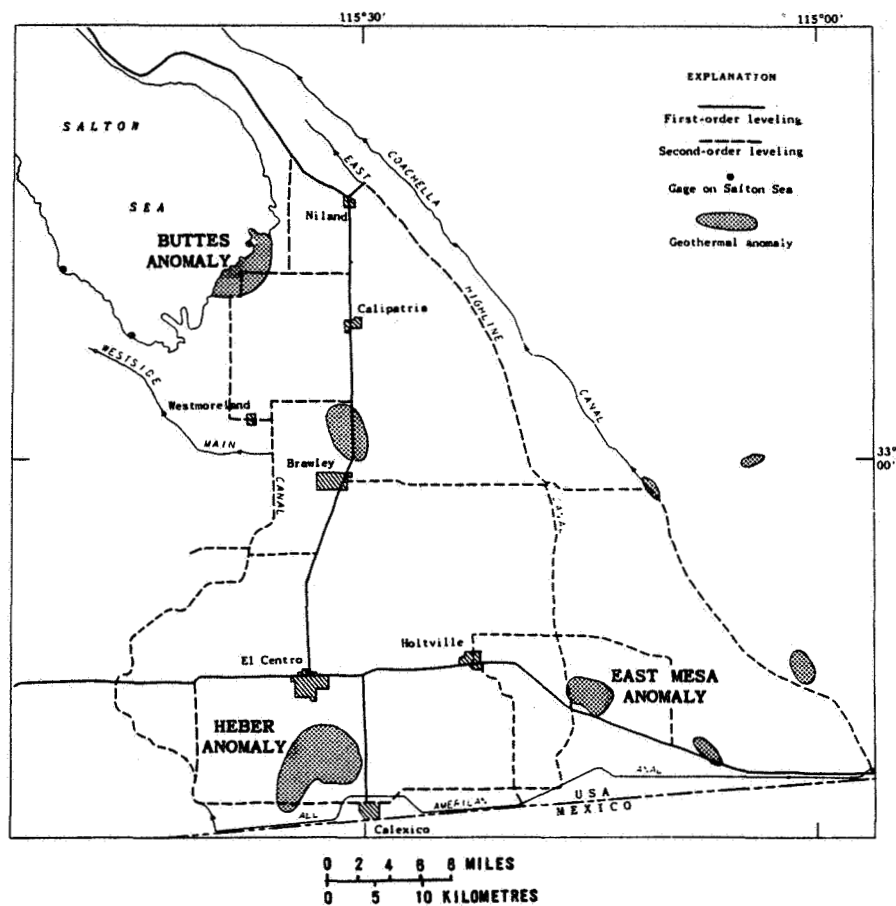


Fig. 1. Location of geothermal anomalies and network of leveling, Imperial Valley, California

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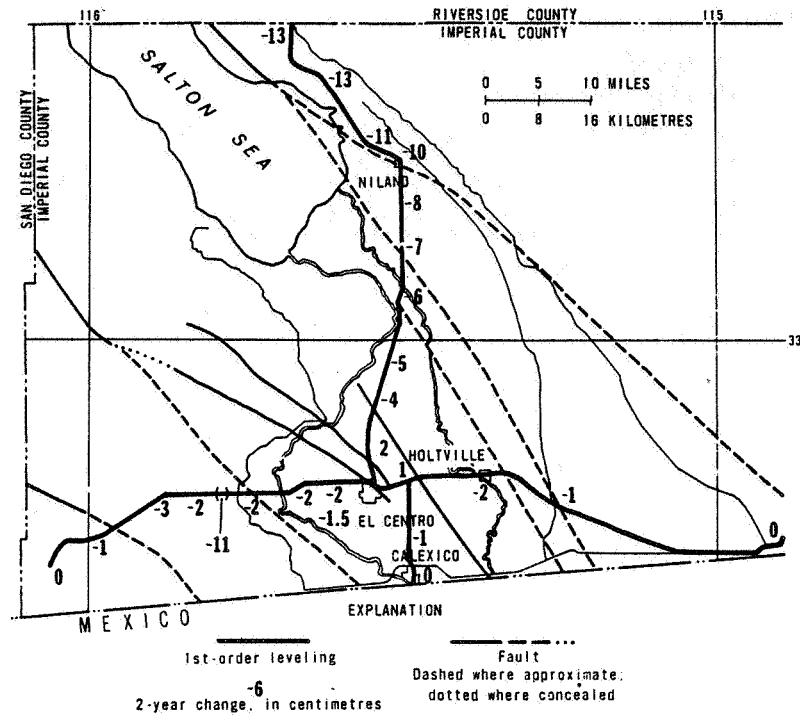


Fig. 2. Network of first-order vertical control and 2-year change in elevation

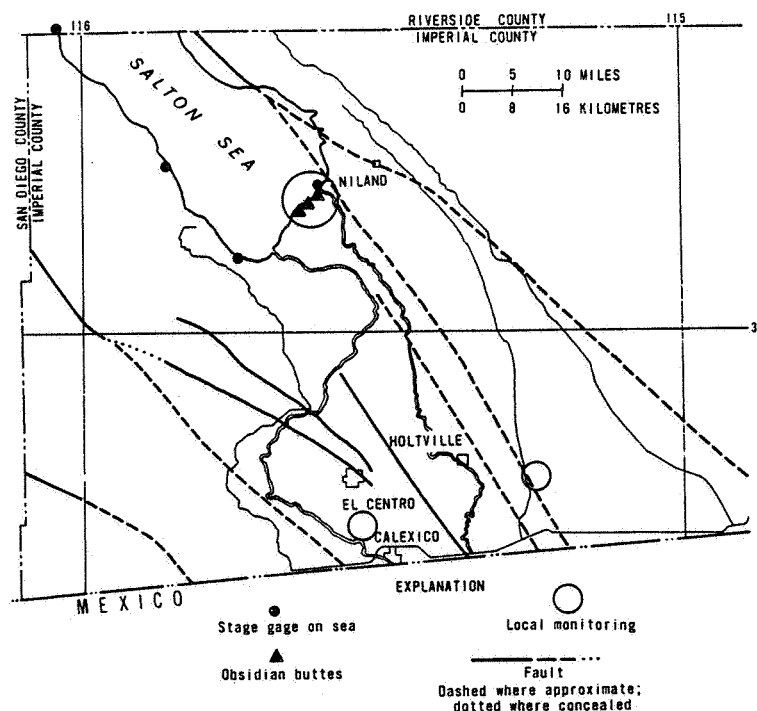


Fig. 3. Geothermal areas of local vertical and horizontal control monitoring

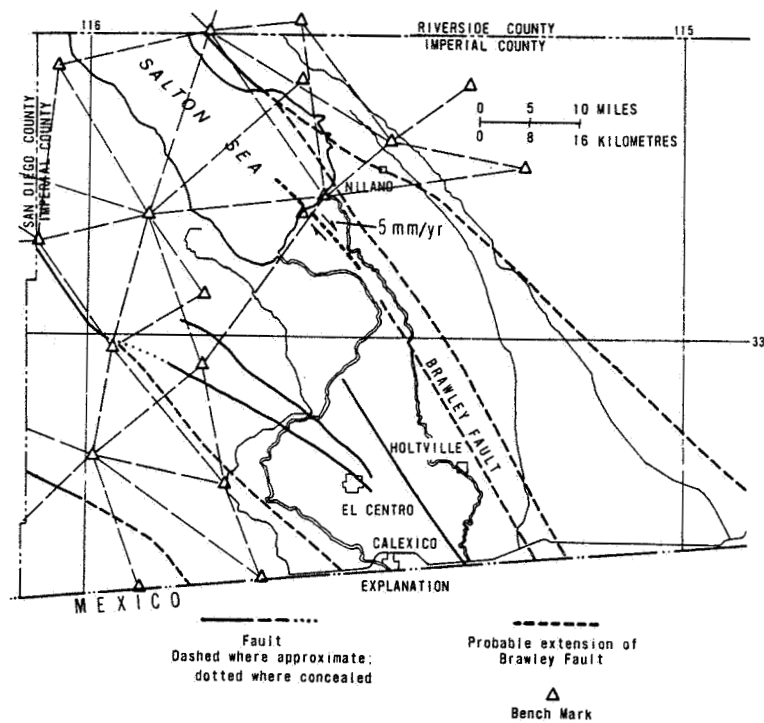


Fig. 4. Regional network of horizontal control

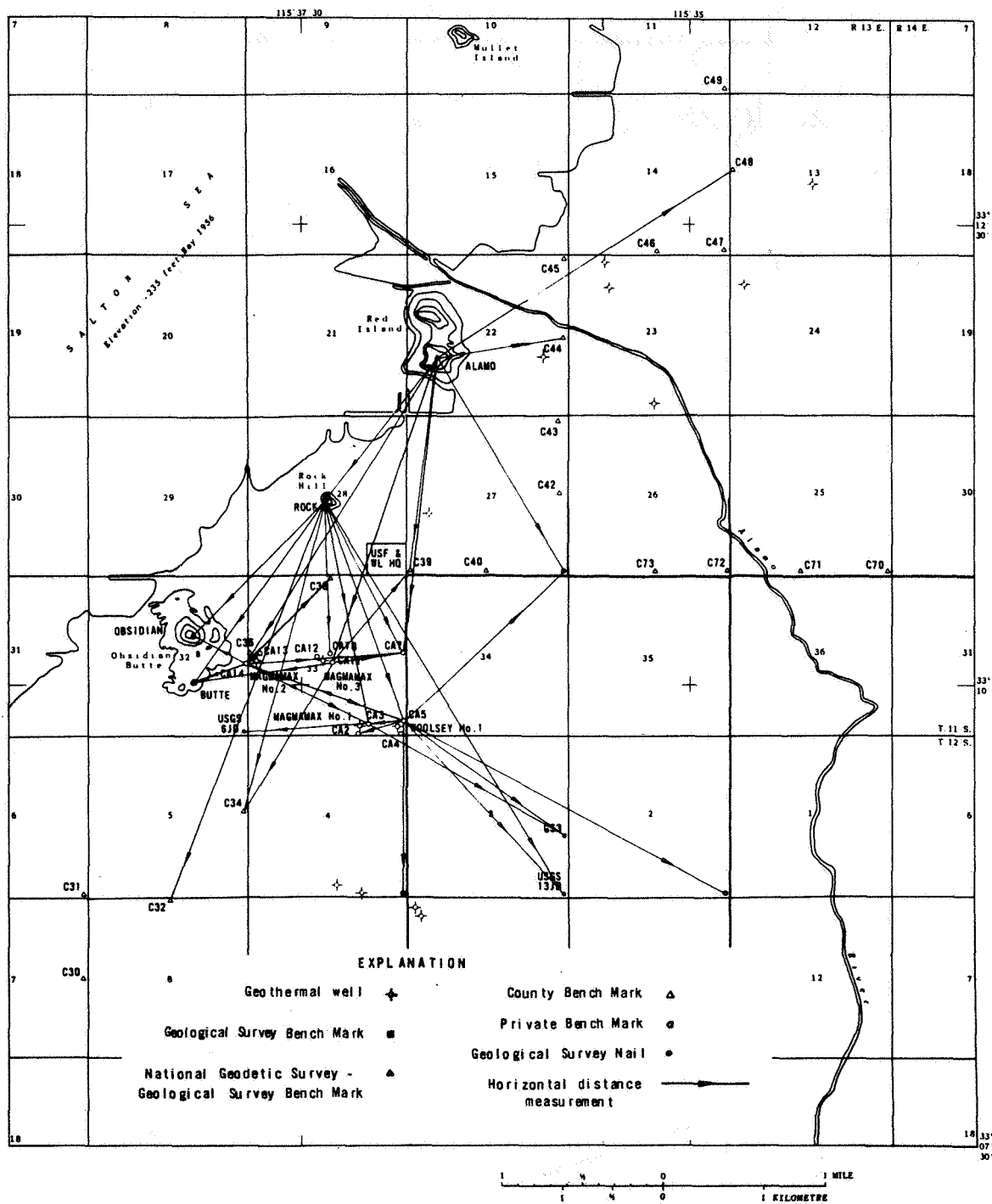


Fig. 5. Network of horizontal control in Buttes area

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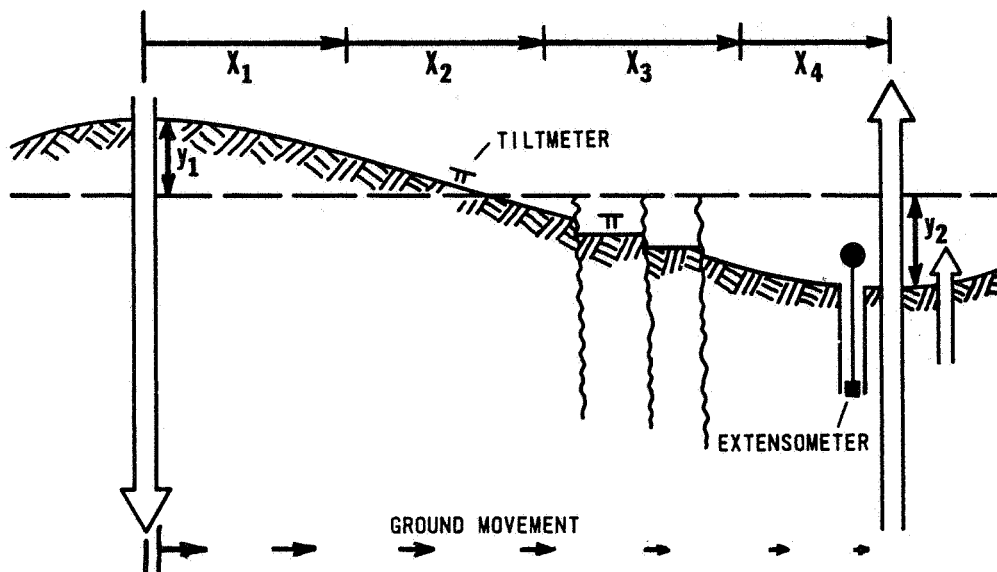


Fig. 6. Surface deformation in an extract-injection area

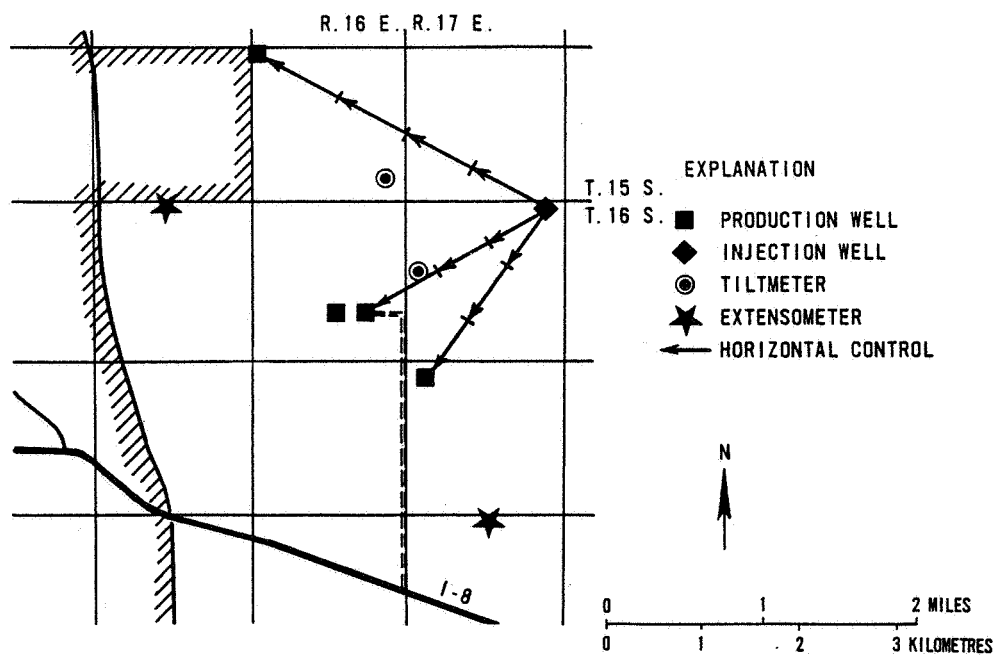


Fig. 7. Instrumentation installed at East Mesa geothermal area

INSTITUTIONAL AND ENVIRONMENTAL PROBLEMS IN GEOTHERMAL RESOURCE DEVELOPMENT

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A number of regulatory and institutional impediments to the development of geothermal energy exist. None of these seem likely to prevent the development of this energy source, but in the aggregate they will pace its growth as certainly as the technological issues. The issues are associated with the encouragement of exploration and development, assuring a market for geothermal steam or hot water, and accomplishing the required research and development in a timely manner.

The development of geothermal energy in the United States at a high level is apt to cause both favorable and unfavorable, though manageable, impacts which can be grouped into eight major areas.

It will change the electric utility fuel mix by substituting for nuclear and coal generating plants.

Two business sectors will be stimulated by geothermal development. These are businesses involved in the exploitation of geothermal energy and businesses which can uniquely utilize geothermal resources.

Macroeconomic and societal factors will be affected. Development of geothermal energy provides a way of helping to meet demand and geothermal sources seem likely to furnish about 10 percent of the total demand for electricity by the end of the century.

The development of geothermal energy will help bring about a national electrical grid.

It is essential that certain institutional arrangements change if the development of geothermal energy is to be accelerated. Currently, federal, state, and local regulations, particularly environmental regulations, overlap and cause delays.

The impacts on regions and cities stem from industrialization resulting from the development of the geothermal resource itself and from the potential influx of businesses which support

geothermal development and which can utilize the heat and mineral content of the geothermal fluids.

Geothermal energy will affect international relations. At least 70 countries have geothermal potential. Technological aid and geothermal markets can be expected to develop as early as the late 1970's.

Some environmental issues have important local but temporary significance and others have potentially lasting significance (e.g., contamination of groundwater supplies, seismicity, and subsidence). The extent of the potentially irreversible environmental impacts is not known with precision.

I. INTRODUCTION

A number of institutional and regulatory impediments to the development of geothermal energy exist. None of these seem likely to prevent the development of this energy source, but in the aggregate, they will pace its growth as certainly as the technological issues. The issues are associated with the encouragement of exploration and development, assuring a market for geothermal steam, hot water or electricity, and accomplishing the required research and development in a timely manner.

The development of geothermal energy in the United States at a high level is apt to cause both favorable and unfavorable, though manageable, impacts which can be grouped into eight major areas which are discussed in this paper.

Geothermal energy can be a relatively important energy source in the United States by the year 2000. It could supply 190,000 to 250,000 MWe, compared to an expected U.S. total capacity of 2 million MWe. At this level, by 2000 geothermal sources will be contributing more to our energy supply than hydroelectric sources.

Because geothermal sources are located primarily in the western part of the United States, the effects of geothermal energy will be considerably greater there than elsewhere in the United States. For example, total electricity generation capacity in the western part of the United States is expected to reach about 480,000 MWe by the year 2000; geothermal sources can constitute 25 percent or more of the total supply in that region.

The contribution of geothermal resources to U.S. energy supplies seems likely to increase continuously; by 1985 it is reasonable to expect that geothermal sources will be producing 7000 to 20,000 MWe or so out of a total of about 1 million MWe in the United States. After 1985, growth could be very rapid. The use of geothermal energy for space heating and for process heat can be very substantial and requires much further attention.

II. ELECTRIC UTILITY FUEL MIX

The electric utility fuel mix will be changed by substituting for nuclear and coal generating plants. The development of geothermal resources could lead to (by 2000) fewer nuclear plants (100,000 to 150,000 MWe could be saved) and fewer coal-fired plants (90,000 to 120,000 MWe could be saved). In total, these savings amount to about 15 percent of the country's coal and nuclear generation capacity by the end of the century. Thus, while geothermal development has an important effect on these generating sources, it is by no means pre-emptory.

These shifts in fuel mix are likely to bring a number of secondary impacts, such as reduction in the number of nuclear and coal-fired generation sites, reduction in the amount of radioactive material to be stored, reduced need for mining of coal for use in electrical generation, and so on.

III. EFFECTS ON BUSINESS

Two business sectors will be stimulated by geothermal development. These are businesses involved in the exploitation of geothermal energy and businesses which can uniquely utilize geothermal resources. The total investment in geothermal development (materials, land, equipment, and so on) could be on the order of \$95 billion by the year 2000. The business affected by the advent of geothermal energy will be largely those which can utilize geothermal heat directly. Various business uses of geothermal energy are listed in Table 1 and policies to optimize the uses are suggested in Table 2.

A business which utilizes geothermal heat is, in effect, utilizing hot water. Hot water can come from many other sources (e.g., cooling water effluent); thus, development of a technology which permits the use of waste heat is directly applicable to geothermal fluids. Businesses which utilize geothermal electricity could, as well, utilize electricity from other sources; one kilowatt is indistinguishable from another. The effect on such businesses will be only that realized as the result of increased availability of electricity.

A major consequence of direct use of geothermal heat will be to bring certain industrial plants near the source of geothermal heat. Flowing from this impact will be a host of higher order impacts associated with land use, demographic shifts, regional economics, and so on. Since the extent of geothermal resources is not yet clearly known, and since it is apparent that the first use of geothermal energy will be for the production of electricity, it is difficult to project the intensity of these impacts; however, the effects of these impacts probably will not be large when viewed on a national scale. From the standpoint of the affected localities, however, impacts could be similar to those associated with mild industrialization and therefore could be viewed by various interest groups as being beneficial or detrimental as a result of changing land use patterns, increasing population density, creation of the need for new public services, increasing the tax base, increasing the number of jobs, and so on.

IV. MACROECONOMIC AND SOCIETAL FACTORS

Macroeconomic and societal factors will be affected. It seems certain that the demand for electricity will increase, and development of geothermal energy provides a way of helping to meet that demand. However, since geothermal sources seem likely to furnish about 10 percent of the total demand for electricity by the end of the century, the effect of its price "dilution" will be small. However, the marginal value of the geothermal energy can be significant as shown by Table 3. In this table, two cases forecasted by our power simulation model for the present regular geothermal development (base case) and for the accelerated case (all out development) are presented. The U.S. energy consumption was predicted and combined with the available geothermal energy to ascertain the marginal effect. The effect is significant in the overall economy (e.g., 164.5 billion dollars in year 2000 for the base case). This means that geothermal energy could support 164.5 billion dollars of the gross national product (GNP) in 2000 and thus help support prosperity and standard of living.

Most of the specific societal impacts flowing from the development of geothermal energy will evolve from significant characteristics: the small size of optimum installations and the location of the resources, which, in most cases, are in outlying areas. These factors are illustrated in Table 4.

Federal royalty income from geothermal development (190,000-MWe capacity) could amount to \$1 billion per year by 2000, and local governments could realize about \$475 million per year from local taxes by 2000. These sums are helpful but not overwhelming; for comparison, federal tax revenues in 1971 were \$137 billion and local tax revenues \$43 billion.

V. NATIONAL ELECTRICITY GRID

The development of geothermal energy will help bring about a national electrical grid. Using reasonable estimates of the cost of constructing and operating a transcontinental high-voltage dc transmission line, electricity derived from geothermal sources in the West can be supplied to the mid-West and eastern portion of the United States at a cost of about 25 mills (1973) per kWh in 2000. Based on considerations of reliability, continued supply, diversity, and capital requirements, it is plausible to expect mid-western and eastern utility companies to purchase on the order of 56,000 MWe (out of a demand of 1.6 million MWe in the East) of geothermally generated electricity from western sources by the year 2000. Table 5 illustrates forecasts made in the power simulation model.

This transportation of electrical energy from west to east will take advantage of intercontinental lines likely to be in place in support of coal minemouth generation plants. The important secondary impacts flowing from this development include increased R&D development in the fields of high-efficiency, high-capacity transmission lines, and esthetic effects which seem likely to arouse conflict. Cost considerations seem to preclude placing transmission lines underground; however, the use of hydrogen produced from electrolysis of geothermal electricity may be an economic alternative to high-voltage dc transmission.

VI. INSTITUTIONAL ARRANGEMENTS

The complete flowchart of institutions concerned with developing geothermal energy is shown in Fig. 1. It is essential that certain institutional arrangements change if the development of geothermal energy is to be accelerated. Currently, federal, state, and local regulations, particularly environmental regulations, overlap and cause delays.

At the federal level, research and development and programmatic planning is being accomplished by an Interagency Panel for Geothermal Energy Research composed of the National Science Foundation, the Department of the Interior, the Atomic Energy Commission, and the Department of Defense. As the geothermal program develops, these groups may have some divergent and conflicting interests; the implementation of an energy R&D agency (ERDA) will also make this panel obsolete.

The geothermal law, as presently constituted, encourages the participation of large companies and discourages small companies. For this reason a significant institutional impact is expected to be the increasing participation in geothermal development of major petroleum companies.

Arrangements developed in the past for selling other forms of energy may not be adaptable to this form and indeed may hinder its development. As the system is presently constituted, utility companies are the only major buyers of geothermal energy. A major problem issue is insuring an adequate flow of money to finance the timely geothermal development. This is illustrated by Figs. 2 and 3.

VII. REGIONS AND CITIES

Geothermal development will affect regions, cities, and buildings. The impacts on regions and cities stem from industrialization resulting from the development of the geothermal resource itself and from the potential influx of businesses which support geothermal development and which can utilize the heat and mineral content of the geothermal fluids. At the secondary level this results in changing population levels, population density, and land use patterns. However, these changes also bring an increased tax base, a potentially cleaner environment, and increased employment. Cities near geothermal resources will have the opportunity to develop district heating. Reykjavik, Iceland, which now supplies almost all of its residents with inexpensive geothermal heat, can serve as an example. District cooling systems have not yet been attempted anywhere in the world, but cooling of a tourist hotel in New Zealand using geothermal heat as an energy source establishes the feasibility of such an approach.

VIII. INTERNATIONAL RELATIONS

Geothermal energy will affect international relations. At least 70 countries have geothermal potential. Some of these countries have already

developed a portion of their geothermal resources; others have not. Development of geothermal technology in the United States will not only create the opportunity for technological aid, particularly to countries with relatively low GNP per capita, but it will lead to the creation of new markets throughout the world. Technological aid and geothermal markets can be expected to develop as early as the late 1970's. When foreign countries develop indigenous geothermal resources, their demand for imported fuel will diminish. Similarly, as the United States develops geothermal energy, fuels which might have been used for the generation of electricity can be put to other uses (or not mined or imported at all). The impact is significant: geothermal energy "frees up" enough coal for export to bring into the United States a total of between \$13 and \$20 billion (cumulative) by the year 2000. The effect on U.S. oil imports is even more dramatic as shown by Table 6 and Fig. 4. By 1994, accelerated geothermal development could save importing 1 billion barrels oil per year equivalent.

IX. ENVIRONMENTAL ISSUES

If geothermal technology is developed under existing economic constraints, the evolution of pollution control technology will probably keep pace. Adequate environmental rules and regulations are presently on the books to ensure only nuisance level impacts if all leasing, pollution control, and monitoring procedures are literally applied. Most states have promulgated ambient air quality standards which often exceed federal standards. Except for accidents, geothermal sources should not exceed these limitations for more than short periods of time. Hydrogen sulphide emission from steam and hot water sources can be reduced to safe levels by natural dispersion and dilution or, if necessary, by a scrubbing apparatus expected to be available shortly.

Contamination of surface water by geothermal operations is a potential problem, but with careful study it should be possible to avoid unanticipated or irreversible consequences.

Seismicity and subsidence are possible geothermal issues of considerably more concern. As much information as possible should be developed about these issues on a theoretical basis. When deep injection is to take place in areas where faults are likely or possible, or when reinjection is possible, seismicity and subsidence should become primary foci of environmental impact analyses.

The extensive geothermal provinces which have been identified to date are predominantly of the liquid-and-vapor-dominated reservoir type. These resource types are expected to produce a major portion of the geothermal power output in the future. Therefore, under a crash program, it could be assumed that rather large tracts in sections of California, Washington, Oregon, Nevada, Arizona, New Mexico, and others would be thoroughly explored and developed into multiple-unit power generating complexes with interconnecting transmission lines. The intermingling of these plants with mineral extraction plants, water reclamation units, and other related industries could result in refinery-type complexes, with interconnecting pipelines, building, water holding ponds, and cooling towers which might, in some areas,

cover several square miles. Of course, high-voltage transmission lines would be installed in these developments also. Based on the forecast energy development assumptions, a maximum of approximately 1500 to 2500 square miles of surface will ultimately be required to accommodate the development of all of these geothermal and ancillary facilities.

Although the indications are that the environmental impacts created out of the development of geothermal energy are not of major significance when compared to other energy forms, it is desirable to evaluate these possible environmental impacts in a summary manner. This was done and is presented in Fig. 5. The relative significance of these impacts was based on the numerical key as shown in the figure. The numbers in the figure represent the consensus opinion of the study team and the panel of consultants.

The two most important environmental impacts were judged to be contamination of surface and subsurface waters and seismicity. It is no coincidence that these two impacts are also judged to be the most important in the Department of the Interior environmental statement for the geothermal leasing program. The points made in this study are similar to those made in the Department of the Interior statement.

The impacts listed in the figure summarize the discussion of this section. The weightings given to the columns on lasting qualities and timing indicate the importance for making adequate and timely plans at the beginning of the geothermal energy development. By doing this it appears that environmental disruption can be kept to a minimum while the geothermal resource can be a valuable domestic energy component.

X. IMPACT ON INTEREST GROUPS

Detailed assessment of selected potential impacts indicates that the interest groups in society most likely to support geothermal development because of the benefits it provides are the financial community, the U.S. Government, businesses that supply the geothermal industry, the geothermal industry itself, and the new research community involved in geothermal research. The groups likely to react to the threats of geothermal energy are environmentalists, the Environmental Protection Agency, groups of homeowners near geothermal installations, and the utility companies affected by the transcontinental grid. Lists of the more important positive and negative impacts are presented in Tables 7 and 8. The policies likely to be viewed most desirable (that is, policies which increase the perceived positive consequences, minimize the perceived detriments, and promote agreement among the groups involved) are those which address the environmental implications of the use of the resource and help to resolve potential land use conflicts.

ACKNOWLEDGMENT

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Table 1. Business uses of geothermal energy

BUSINESSES THAT UTILIZE ELECTRICITY

General Industrial Consumption

Heavy Users of Electricity

Aluminum

Chemicals

Electrified Railroads

Agriculture

BUSINESSES THAT UTILIZE PROCESS HEAT

Greenhouses

Fish Farms

Field Crops – Soil Warming

Food Processing – Canning and Freezing

Paper and Pulp

Chemicals

Lumber Drying

Grain Drying (Corn and Wheat)

Animal Husbandry

Water Desalination

Table 2. Policies to optimize impacts on business

Basic research in utilization of process heat

Dissemination of information on use of geothermal heat and electricity

Local or regional backing of industrial parks where small firms can utilize geothermal energy, with possible federal loan assistance

Federal loans or subsidies for developmental geothermal projects

Federal assurance of flow-through of benefits of subsidies or loans to geothermal developers to ultimate users

Federal reliability insurance to ultimate users

Extension of oil and gas tax benefits to geothermal developers

Allocations of scarce supplies to geothermal developers who may not have purchasing history

Assistance to educational programs for geothermal specialists

Table 3. Marginal effect of geothermal availability on energy-limited United States gross national product

Year	Geothermal energy, 10 ¹² Btu		U.S. energy consumption, 10 ³ Btu/\$ GNP	Marginal effect of geothermal on GNP, 10 ⁹ dollars	
	Base program	Accelerated* program		Base program	Accelerated program*
1980	0.26	0.38	81.4	3.2	4.7
1985	0.42	1.25	79.5	5.3	15.7
1990	1.34	3.33	77.5	17.3	43.0
1995	4.47	7.51	75.7	59.0	99.2
2000	12.17	15.97	74.0	164.5	215.8
*Accelerated program is one in which virtually all technological and nontechnological impediments are removed.					

Table 4. Macrosocietal factors

Maintenance of life style based on abundant energy
Redistribution of population
Local societal changes resulting from changing economic base
Local educational changes resulting from changing economic base
Effects of changes in pollution levels on health
Changes in recreational patterns

Table 5. Assumptions and forecasts of baseline scenario relevant to transcontinental electrical grid (1000 MWe)

Assumptions and forecasts	Year	
	1985	2000
Geothermal electricity capacity in the West	7	147
Geothermal electricity capacity in the East	0	41
Geothermal electricity transported West to East	0	56
Cost of geothermal electricity in the West (constant 1973 dollars)	10.4 mills/kWh	14.5 mills/kWh
Cost of geothermal electricity transported to East (2500 miles) (constant 1973 dollars)	19.3 mills/kWh	25.7 mills/kWh
Number of transcontinental corridors in operation (assuming standard FPC reliability criteria)	0	4

Table 6. Oil equivalent of geothermal energy

Year	Amount of energy			
	MWe		Annual millions of barrels of oil equivalent	
	Base	Accelerated	Base	Accelerated
1973	0.40	0.40	4.21	4.21
1976	0.73	0.73	7.68	7.68
1979	3.59	4.10	37.78	43.15
1982	4.82	9.26	50.73	97.46
1985	6.58	19.50	69.25	205.24
1988	13.39	36.79	140.93	387.21
1991	24.68	59.74	259.76	628.76
1994	54.67	96.94	575.40	1020.29
1997	108.33	158.44	1140.17	1667.58
2000	188.11	249.22	1979.85	2623.04

Table 7. Impacts which are likely to be perceived as having greatest positive consequences

Increased geothermal R&D for the environment

Improvements in inflation over a "nongeo-thermal world"

Lower than expected price for electricity

Improvements in GNP over a "nongeothermal world"

Improvements in government income over a "nongeothermal world"

Decreasing rate of depletion of oil

Decreasing rate of depletion of gas

Increased geothermal R&D exploration

Diminishment of the amount of imported energy

Movement of businesses that use geothermal electricity, heat, or minerals into geothermal regions

Table 8. Impacts which are likely to be perceived as having greatest negative consequences

Increased possibility of seismicity near geothermal installations

Increased possibility of land subsidence near geothermal installations

Delayed development of solar energy

Increasing rate of depletion of geothermal resources

Creation of new opportunities for crime (e.g., destroying geothermal wells)

Diminished air quality near geothermal installations

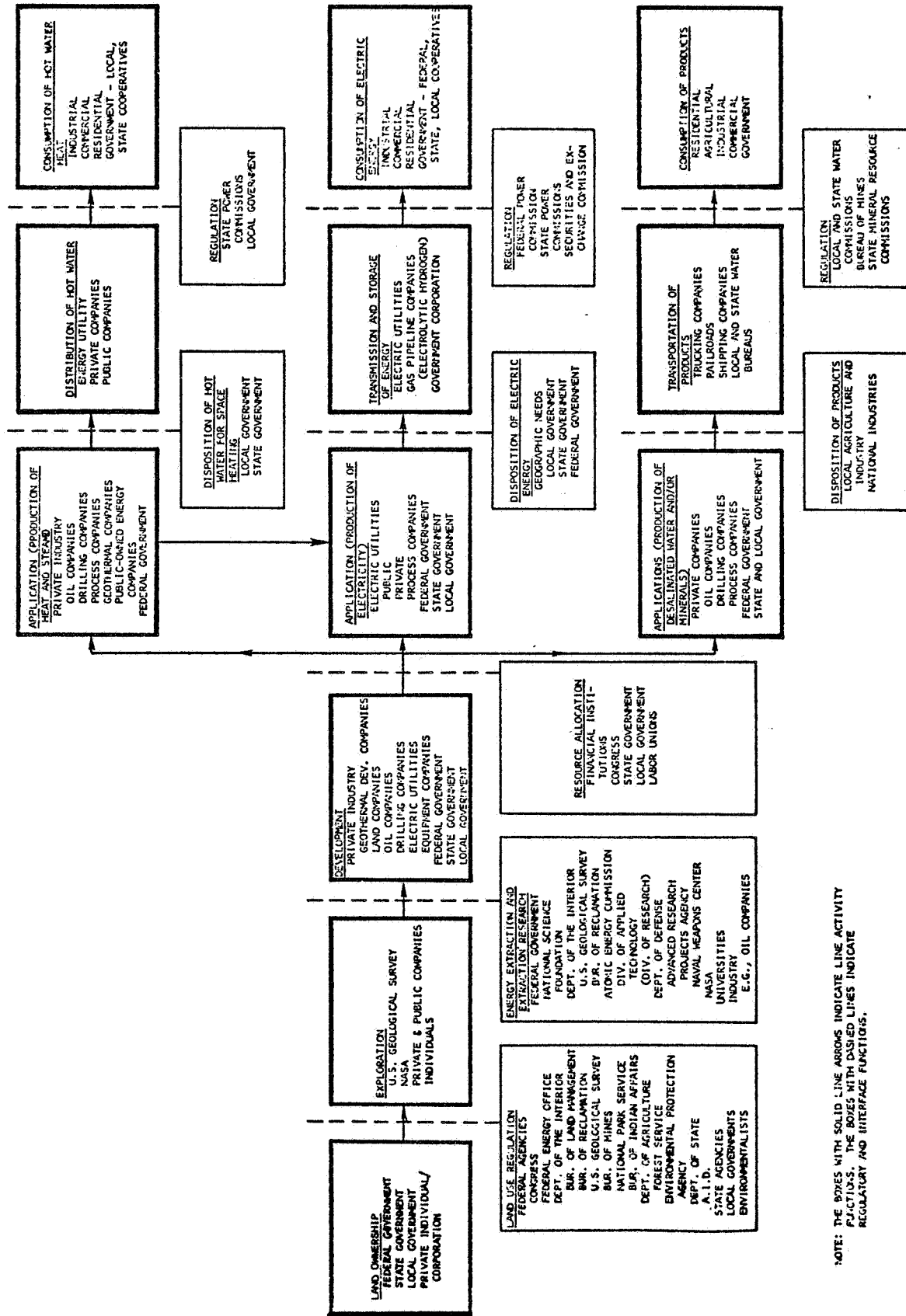
Relocation of local population in order to accommodate geothermal installations

Use of recreation, park, and wilderness areas for geothermal installations

Increased noise near geothermal installations

Diminished water quality near geothermal installations

Use of agricultural and forest lands for development of geothermal installations



NOTE: THE BOXES WITH SOLID LINE ARROWS INDICATE LINE ACTIVITY FUNCTIONS. THE BOXES WITH DASHED LINES INDICATE REGULATORY AND INTERFACE FUNCTIONS.

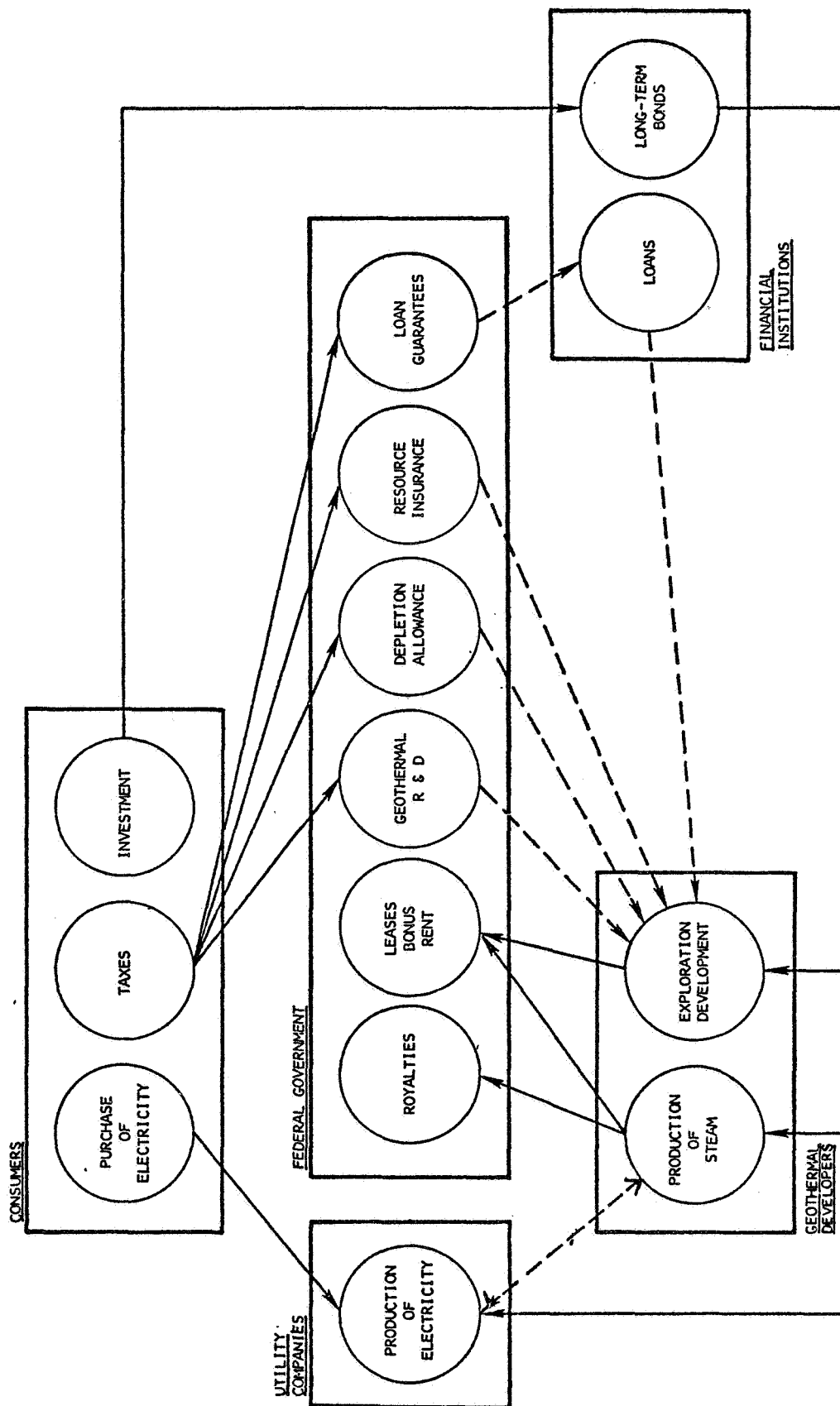
Fig. 1. Institutions having a role in geothermal energy development

PRINCIPLE ISSUE: PROVISION OF CAPITAL FOR A HIGH-RISK,
LONG-TIME RETURN, CAPITAL INTENSIVE
INDUSTRY

POLICIES

- LOANS, SUBSIDIES, INSURANCE GUARANTEES, PURCHASE AGREEMENTS
- TAX INCENTIVES
- DEVELOPMENT OF NEW METHODS OF PRIVATE FINANCING
- DEMONSTRATION OF RELIABILITY IN PILOT PLANTS
- QUASI-PUBLIC DEVELOPMENT CORPORATIONS
- PUBLICLY OWNED GEOTHERMAL PLANTS TO ACT AS INDUSTRY BAROMETERS

Fig. 2. Financial institutional arrangements



NOTE: DASHED LINES INDICATE FACTORS WHICH MODULATE MONETARY FLOW.

Fig. 3. Financial flow

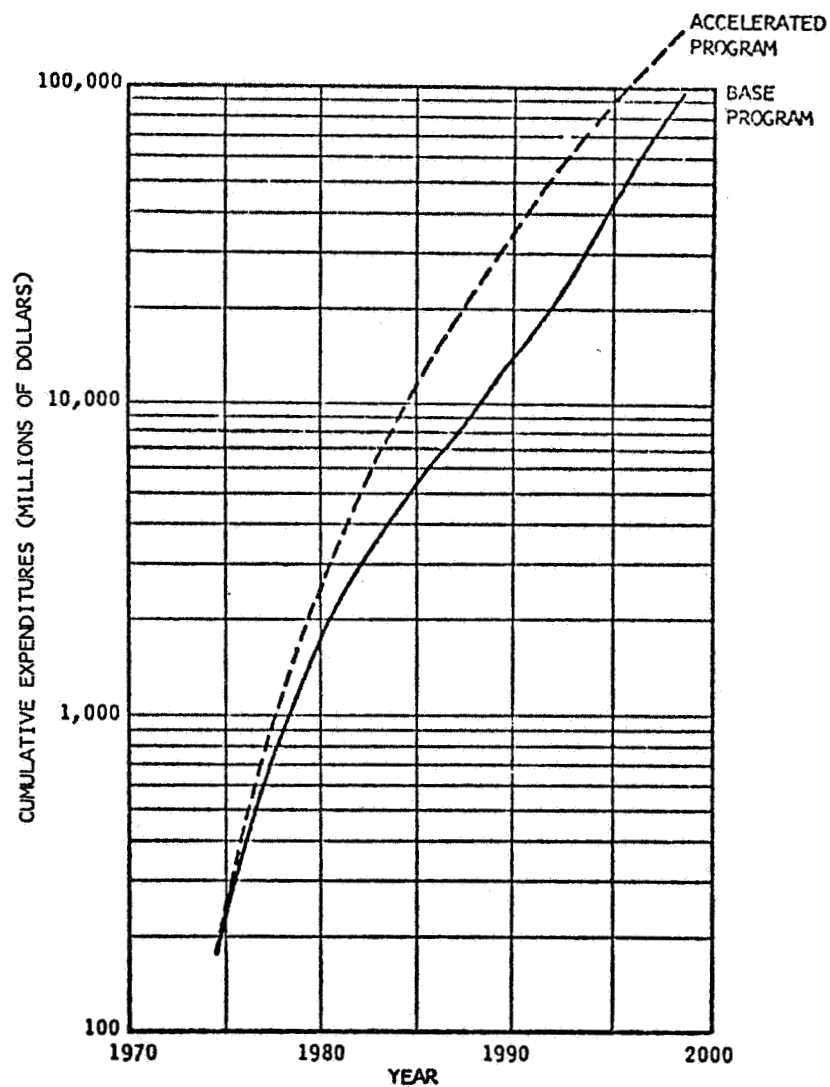


Fig. 4. Cumulative expenditures if forecasted amount of geothermal electricity were produced by oil costing \$10/bbl

IMPERIAL VALLEY'S PROPOSAL TO DEVELOP A GUIDE
FOR GEOTHERMAL DEVELOPMENT
WITHIN ITS COUNTY

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The county's tool to guide its development is a so called "General Plan." The purpose of this project is to establish the geothermal element for the County's General Plan. In order to prepare such a General Plan, a considerable amount of research plus compilation and examination of existing research is required. A proposal is pending wherein Imperial County, University of California, Riverside, and California Institute of Technology would combine efforts to develop this plan. This research should show the general location in which development could occur, the economic tradeoffs of geothermal development, the sociological, geographic, land use, and environmental effects, plus geological and engineering study. When all is put together, we will know what effect geothermal development will have upon Imperial County as determined by the best available evidence at this time.

Imperial County is not only known as the nation's salad bowl but it now is becoming known as the nation's "teapot." The geothermal resource areas of the county are being explored and tested. The various techniques of harnessing the resource are now being researched in the laboratory and in the field. Both industry and the federal government are proceeding to develop a means to utilize the heat and liquids to generate electricity and to produce fresh water.

The people and the government of Imperial County look on this process with considerable interest. We need certain kinds of development, but we do need to insure compatibility with our current environment. The county government has just applied to the National Science Foundation for funds to study the effects of geothermal development in the county and to prepare a geothermal element of the County General Plan.

Some of you may be familiar with the California General Plan Requirements but for those who are not, I can briefly summarize. The General Plan is to consist of development policies and shall include text and graphics setting forth the objectives, principles, standards, and proposals. The geothermal element, when adopted, would be the guide for development. It would allow the developers to know what the goals of the county are and would give the county decisionmakers a tool to use on developers. In order to understand the problem, a summary of the county should be given.

Imperial County contains one of the more unusual agricultural areas in the world. Here in the middle of an actual desert lies Imperial Valley, which can produce over a third of a billion dollars in crops and livestock annually. It is possible to produce up to four crops a year on some pieces of land because of the warm and extremely long growing seasons and the fact that the land is almost totally supported by irrigation water from the Colorado River. The irrigation water flows via the All American Canal to the center of the valley then flows northward via canals on the east and west edges of the irrigated area. There are 655,680 acres between the two eastern and western canals, and approximately 474,500 acres are in actual agricultural production. The county as a whole has approximately 4600 square miles, so the irrigated area is approximately 25 percent of the county.

Imperial County is also blessed with large acreage designated as geothermal resource areas. The Glamis, the Dunes, and the East Mesa KGRA's are outside the irrigated area and on principally government land. The Heber, Brawley, and the Salton Sea resource areas lie within the irrigated area and underlie privately owned land.

The County Board of Supervisors has adopted several policies concerning the relationship between agricultural land and geothermal development. In the "Terms, Conditions, and Standards for Initial Geothermal Development in Imperial County," adopted in 1971, it is stated that "it is the intent of this policy to encourage exploration and development projects, and to increase the store of knowledge surrounding this resource." The Ultimate Land Use Plan states that "agriculture is the current mainstay of Imperial County's economy; therefore, in order to achieve the General Plan goals, it is imperative that the agricultural land be guarded against noncompatible use." This policy was adopted on June 25, 1973.

Imperial County felt a specific responsibility to the people of the county to guide initial geothermal development within the county. The county assumed this responsibility through the zoning regulations as a means of control. Many of the KGRA's are on private lands, where the county's zoning controls are not questioned. In addition, the county has requested that our standards be imposed when the federal government issues geothermal leases.

In order to implement the zoning regulations, the County of Imperial prepared a series of "Terms, Conditions, and Standards for Initial Geothermal Development" and adopted it as a public policy for this development. It is the stated intent of this policy to encourage exploration and development projects and to increase the store of knowledge surrounding this resource. It is also the intent of this policy that there be coordination of existing anticipated data so that general planning may occur to provide the optimum development of the resource.

As described before, we want development compatible with our agriculture. The county now appears to be on the verge of an almost major geothermal development. The terms, conditions, and standards were satisfactory for individual exploratory wells, but they are not enough to evaluate a 50-megawatt generating plant with 10 geothermal wells.

To fill this void, the county approached the University of California at Riverside and the California Institute of Technology, Pasadena, to determine if they could assist us in preparing a geothermal element for the General Plan. It was realized early that most of the information needed to prepare such an element was not available. So the first order of research would be to study the effect of various types and sizes of development on all areas of the county. After this is done, we would be in a position to prepare the actual element.

In order to fund the basic research and the element, the county, with the very great assistance of the University of California, Riverside, has prepared a Grant Application and submitted it to the National Science Foundation, and we expect favorable action.

This geothermal research will be conducted by members of the faculty of the University of California, Riverside, and the California Institute of Technology in Pasadena. We will utilize the talents of geophysicists, engineers, sociologists, economists, geographers, and public relations experts to conduct research and to produce the following:

- (1) A geothermal element, which shows the proposed locations, zoning, and regulations of geothermal development.
- (2) An economic tradeoff study, which shows who gains and who loses from geothermal development by economic sector.
- (3) A sociologic study, which shows the impacts upon employment, families, ethnic groups, social structure, and interest parties affected.
- (4) A policy analysis, which identifies the political issues, alternatives, coalitions, and regulations that may resolve differences of interests.
- (5) A geographic study, which identifies the alternative geothermal well locations, development patterns, land use effects, agricultural losses, and environmental effects.
- (6) A geological assessment, which defines the extent and quality of the resource, in terms of heat, chemical composition, extraction problems, and costs of well development.
- (7) An engineering assessment, which identifies the costs associated with energy collection, conversion, waste water disposal, and environmental abatement.

The county will retain specialized personnel to insure that the answers are meaningful and to prepare the geothermal element. The county will organize an industrial committee made up of representatives in the geothermal industry area who will monitor progress and express industrial concerns. We will also establish a management committee made up of county officials who will insure inclusion of the county's interests. Each of these committees will have a periodic overview of the research progress and will be able to detect undesirable directions of research.

Once all this research is completed, the geothermal element will be prepared and, after multiple public hearings, will be adopted as county policy.

This plan will be prepared in such a manner that it will provide a roadmap for development of this resource or similar resources in other counties. In addition, the techniques used in research will also be transferable. Thus, once again, Imperial County may be used as a model in this field. We feel that we are progressive, small enough to be flexible, and large enough to be capable. This combination of county government is not always available. We consider ourselves fortunate to be able to interest NSF and the educational institutions in this problem, and we would expect this project to be invaluable to the County of Imperial and to other developable areas.

SESSION IV

RESOURCE UTILIZATION PROJECTS

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SESSION IV. RESOURCE UTILIZATION PROJECTS

SESSION CHAIRMAN: D. H. Stewart

THE LAWRENCE BERKELEY LABORATORY GEOTHERMAL PROGRAM IN NORTHERN NEVADA – K. F. Mirk and H. A. Wollenberg

THE TOTAL FLOW CONCEPT FOR GEOTHERMAL ENERGY CONVERSION – A. L. Austin

SAN DIEGO GAS & ELECTRIC COMPANY IMPERIAL VALLEY GEOTHERMAL ACTIVITIES: A STATUS REPORT – T. C. Hinrichs

PROGRESS OF THE LASL DRY HOT ROCK GEOTHERMAL ENERGY PROJECT – M. C. Smith

THE MARYSVILLE, MONTANA GEOTHERMAL PROJECT – W. R. McSpadden, D. H. Stewart, and J. T. Kuwada

PRELIMINARY RESULTS OF GEOTHERMAL DESALTING OPERATIONS AT THE EAST MESA TEST SITE, IMPERIAL VALLEY, CALIFORNIA – S. H. Suemoto and K. E. Mathias

THE LAWRENCE BERKELEY LABORATORY GEOTHERMAL
PROGRAM IN NORTHERN NEVADA*

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The Lawrence Berkeley Laboratory's geothermal program began with consideration of regions where fluids in the temperature range of 150 to 230°C may be economically accessible. Three valleys, located in an area of high regional heat flow in north central Nevada, were selected for geological, geophysical, and geochemical field studies. The objective of these ongoing field activities is to select a site for a 10-MW demonstration plant. Field activities (which started in September 1973) are described. A parallel effort has been directed toward the conceptual design of a 10-MW isobutane binary plant which is planned for construction at the selected site. Design details of the plant are described. Project schedule with milestones is shown together with a cost summary of the project.

I. INTRODUCTION

The goal of the LBL-UCB geothermal project is to locate, design, and construct a 10-MW (electrical) geothermal pilot demonstration plant, utilizing the low salinity, high-temperature (170-220°C) waters of the northern Great Basin. Concurrently, parameters indicative of such a resource are evaluated by traditional and new geologic, geochemical, and geophysical techniques.

II. LOCATION

The area chosen for the studies, north-central Nevada, is characterized by higher than normal regional heat flow (Ref. 1). Temperatures at depth in some hot spring systems, determined by chemical geothermometers (Ref. 2), exceed 150-170°C. Figure 1 shows the distribution of heat flow in the western U.S., and the region of high heat flow in northern Nevada. Three sites within this region, Buffalo Valley southwest of Battle Mountain, Grass Valley south of Winnemucca, and Buena Vista Valley southwest of Winnemucca are our present centers of activity. These sites, indicated on the location map (Fig. 2), are all essentially on federal land, and each contains an active hot spring system

*Work done under the auspices of the U.S. Atomic Energy Commission.

(Buffalo Valley Hot Springs, Leach Hot Springs in Grass Valley, and Kyle Hot Springs in Buena Vista Valley).

III. GEOLOGIC SETTING

Active hot spring areas and potential geothermal resource sites in the Great Basin are in almost all cases associated with steeply dipping basin-and-range faults (Ref. 3), often at the intersections of two major orientations of faulting. This is exemplified in Whirlwind Valley (Fig. 3), where the ENE-trending Malpais escarpment is intersected by a nearly north-south trending fault zone just to the east of the active Beowawe Hot Springs and their accompanying blowing geothermal wells. The fault zones furnish permeable pathways for downward percolating, meteoric water to reach sufficient depth (4 to 5 km) in a region of high geothermal gradient (40 to 60°C/km). The water is heated, then rises on the upward-flowing limb of a convection cell (Fig. 4). Thus, fracture permeability, afforded by intersecting faults in sub-alluvial bedrock, is the mechanism by which waters can reach depths great enough for heating, and provides channelways for upward transport of hot waters. Geothermal reservoirs may be in fractured rock of fault zones, or in relatively permeable beds of Tertiary sedimentary deposits and Quaternary valley fill alluvium.

IV. FIELD ACTIVITIES

Our site evaluation program combines interrelating geologic, geophysical, and geochemical studies. Interpretation of high-, middle-, and low-altitude aerial photography (much of it provided by NASA), together with surface geologic mapping, disclose the geologic structure of the areas. This information is used to orient geophysical traverses and interpret their results. Concurrently, sampling of country rock and hot-and-cold spring waters, and their subsequent analyses by x-ray fluorescence and neutron activation techniques yield major- and trace-element contents. Information from the geological, geophysical, and geochemical activities is combined to locate several 100- to 150-m deep heat flow holes in each of the areas under study. Results of the heat flow measurements will, in turn, strongly influence the locations of one or more deep test wells (1.5 to 2 km), which may furnish the fluid for a preliminary heat-exchanger test facility.

A. Geologic Methods

Because much of the area is in valley fill alluvium, reconnaissance and detail mapping relies heavily on the aforementioned aerial photography. High-altitude (65,000 ft) flights by NASA U-2 aircraft provide regional coverage of high-resolution black and white photographs at low sun angles (Fig. 3 is an example), enhancing fault-related features on the desert floor. Lower-altitude (6,000 ft above surface) color photography at higher sun angles shows detail associated with faulting on the immediate site areas. A structural map of the Leach Hot Springs area, compiled from aerial photography and surface observations, is shown as Fig. 5. Airborne infrared imagery, obtained in predawn

hours, indicates well the known hot spring areas, as well as disclosing a hitherto unknown warm-spring area in the west portion of Buffalo Valley playa.

Mapping and age dating of ancient hydrothermal manifestations and related volcanic rocks in the Leach Hot Springs area and the East Range suggest that these silicified zones, 14 to 16 million years old, are residues of hydrothermal systems that produced many precious metal deposits in northern Nevada (Ref. 4).

B. Geophysical Methods

Geophysical techniques used, or planned to be used in evaluation of the sites, are listed on Table 1. Of these, electrical resistivity methods have been employed most heavily to date in our site evaluations. An example of results of a bipole-dipole resistivity reconnaissance in Buffalo Valley is shown on Fig. 6. With the current transmitter at the location in Fig. 6, voltages measured throughout the valley furnished a rather featureless apparent resistivity map, with lowest values associated with electrically conductive playa deposits, and higher resistivities with the nearer-surface and exposed bedrock. A similar pattern was obtained with the current dipole at a different location and reoccupation of the voltage measurement points. A dipole-dipole traverse of the valley yielded the vertical profile pseudosection of resistivity and the accompanying model shown on Fig. 7. The resistivity model matches the gravity profile and schematic model constructed by Grannell (Ref. 5) for the same region. Good concordance has been observed between telluric, self-potential, and dipole-dipole resistivity traverses in the strongly faulted area near Leach Hot Springs. In contrast to the Buffalo Valley pattern, order-of-magnitude differences in resistivity over short distances, indicating, most likely, the presence of warm waters, are apparent at Leach. Magnetotelluric and telluric measurements were made along resistivity profile lines crossing Buffalo Valley with good agreement between results of these methods.

Microearthquake activity was monitored by an eight-station seismometer array for several weeks at each of the three sites. Preliminary results indicate appreciable activity southwest of Leach Hot Springs in and surrounding a mid-valley graben zone. The region encompassing the sites was monitored by a broader array, confirming the locus of activity at Leach, as well as an active zone on the east flank of the Tobin Range.

Three preliminary heat flow holes have been drilled in Buffalo Valley. One is within the thermal anomaly surrounding the hot springs, delimited by Olmsted, et al. (1974, private communication); the others are well outside the anomaly to establish the background heat flow of the area and to compare it with heat flows previously measured by the USGS in nearby bedrock terranes (Ref. 1).

A radiometric survey was made of these and other hot spring systems in northern and central Nevada (Ref. 6). Several hot spring systems where calcium carbonate is the predominant deposit exhibit relatively high radioactivities, caused by emanating radon-222. Spring systems where SiO₂ strongly predominates as the deposit material are low in radioactivity. An array of

radon alpha-track detectors was installed within and surrounding the radioactive spring area in Buffalo Valley (Ref. 7). Away from the springs, integrated track densities are greatest in thin alluvium, covering the relatively high radioactivity rhyolitic Fish Creek Mountains Tuff, attesting to emanation of radon from the Tuff through the alluvium. The greatest alpha-track densities are in detectors placed closest to the obviously radioactive pools and mounds in the hot springs area.

C. Geochemical Methods

Knowledge of major- and trace-element contents of hot and cold spring waters and country rocks within site areas is important for chemical geothermometry, as well as for the study of interactions of rock with hydrothermal waters. Major element abundancies, determined by the nondispersive x-ray fluorescence method (Ref. 8), provide input for temperature estimates based on silica and alkali element ratios. SiO₂ contents of hot and cold spring waters are used in models (Ref. 9) to determine the degree of mixing of near-surface cold water with rising hydrothermal water. Neutron activation analyses of trace elements (Ref. 10) in waters and rocks may provide "fingerprints" of the rocks through which the waters passed, illuminating their pathways from their source area into and within the geothermal system. Furthermore, knowledge of water chemistry is necessary for plant design, and for evaluation of environmental impact of the development of the geothermal resource.

V. 10-MW PILOT PLANT

In January 1974 a program was initiated at Berkeley to develop a conceptual design for a 10-MW pilot plant to be located at the Nevada site. The primary objective of this design study was to produce a realistic cost estimate and schedule for overall program planning. This study was completed in June of this year and reviewed by Rogers Engineering of San Francisco, the architect and engineering firm selected by the AEC for this initial engineering phase. A brief summary of the results of this design study follows.

Prior to starting the final design study these assumptions were made:

- (1) A binary power cycle.
- (2) Isobutane as the working fluid.
- (3) A wellhead brine temperature of 200°C.
- (4) Brine salinity < 3000 ppm total dissolved solids.

A simplified flow schematic is presented in Fig. 8. Three production wells (each with an output of 375,000 lb/hr) and two reinjection wells are required. Each production well is equipped with a downhole pump to provide sufficient pressure head to the brine to prevent flashing and keep any dissolved CO₂ in solution. Temperature of brine exiting the last heat exchanger section is 235°F, and the entire mass flow of 1.1×10^6 lb/hr is reinjected. A single

brine/isobutane heat exchanger is indicated on the schematic; the actual plant will contain eight shell- and tube-type units connected in series. Each unit has a shell diameter of 5 ft and a tube length of 20 ft. The units are so manifolded that any pair can be isolated for cleaning without interrupting the operation of the remaining units. For cost estimating purposes 304L stainless-steel tubes are assumed, and an overall heat transfer coefficient of approximately $100 \text{ Btu/ft}^2 \times \text{hr} \times \text{deg F}$ is used.

An isobutane condensate temperature of 100°F is assumed, resulting in a hot well pressure of 72 psia. Two condensate feed pumps are included in the design. Each pump is driven by a separate isobutane turbine. In addition to the main feed pumps, a smaller electrically driven feed pump (not shown on schematic) is provided for start-up purposes. The feed pumps supply sufficient head to allow the system to operate in the super critical region. This is done to minimize the "pinch-point" effect in the brine/isobutane exchanger.

A regenerative heat exchanger is included in the design. The purpose of this exchanger is to remove the large amount of superheat contained in the exhaust of the turbines and to transfer this heat to the feed isobutane.

Isobutane vapor leaving the brine/isobutane exchanger is directed to both the main and feed pump turbines. A pressure of 600 psia is maintained at the main turbine inlet by controlling the speed of the feed pump turbines. Brine flow through the main heat exchanger is regulated to maintain a turbine inlet temperature of 370°F . Two types of turbines were considered: an axial flow reaction unit and a radial inflow reaction unit. The radial inflow unit was selected for this conceptual design. This particular turbine is a single-stage unit having an impeller diameter of 23 in. and rotates at 9000 rpm, necessitating a reduction unit between the turbine and generator. The turbo-generator unit is rated at 10 MW; plant auxiliaries consume 2 MW, resulting in a net plant output of 8 MW. Exhaust vapor from the turbines passes through the other half of the regenerative exchanger, where it is cooled about 140°F prior to entering the condenser.

The condenser is located in a dry-type cooling tower. Both wet- and dry-type towers were considered. A dry-type tower results in a higher initial cost and a somewhat lower plant efficiency due to the large fan power requirements. However, both maintenance and environmental problems are greatly reduced with the use of a dry-type tower, and for these reasons this type was selected. A dry-bulb temperature of 80°F is assumed for design study purposes. Condensate returns by gravity from condenser section to the hot well.

Not shown on the schematic is an automatic control system whose design allows the plant to be operated from a remote station located anywhere within the distribution system. All plant operations, with the exception of initial startup, can be performed by this system.

The general arrangement of the various plant components is illustrated in Fig. 9. The three production wells are shown in the background with the main brine pipeline terminating at the eight brine/isobutane heat exchangers located in the foreground. The two reinjection wells are not shown on the pictorial but are located to the viewer's right. In order to provide sufficient head to satisfy

the NPSH requirements of the feed pumps, the condensing section of the cooling tower is elevated. Dimensions of the cooling tower are approximately 100 ft wide by 200 ft long.

The main turbo-generator unit is housed in the building directly to the left of the cooling tower. A 36-in. -diameter line is provided to carry the turbine exhaust to the six regenerative heat exchangers located between the turbo-generator building and the cooling tower. An electrical switchgear yard is shown in the far left corner of the site. Across from the switchyard is a small water storage pond having a surface area of 7200 ft² and a storage capacity of 270,000 gal. The pond is used to furnish auxiliary cooling for small heat loads, such as the generator lube oil system, and to provide fire protection for the installation. Adjacent to the cooling pond is a test pad where research and development work can be carried out under actual field conditions on plant components such as heat exchangers, expanders, and pumps. The entire plant facility as shown occupies approximately five acres.

A cost estimate summary is presented in Fig. 10. The first six items were estimated by Rogers Engineering and essentially represent the cost of the power plant. The item "Isobutane System" includes the brine/isobutane heat exchangers, regenerative exchanger, instrumentation and controls, plus all the isobutane piping. "Turbine/Generator" includes the feed pumps and their drivers. The cost of the main condenser is included in the "Cooling Tower" cost. "Production/Reinjection Wells" includes the cost of the downhole pumps. Escalation was calculated at 12% per year for a period of 2-1/2 years. A contingency of approximately 22% based on the escalated cost has been included.

The overall project schedule and logic is shown in Fig. 11. The diagram is self-explanatory and, therefore, little comment is required. Final site selection is scheduled for the end of 1975, at which time the final engineering phase of the project will start. A production and reinjection well drilling program will be started in 1976 and completed by the middle of 1977. Plant components will be fabricated in 1977 and installed and tested in the first half of 1978. Start-up operations are scheduled for the third quarter of 1978.

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Table 1. Geophysical methods

Deep resistivity	Heat flow
Magnetotellurics	Airborne multispectral
Tellurics	Radiometric
Electromagnetics	Gravity
Microearthquakes	Magnetics
Seismic noise	

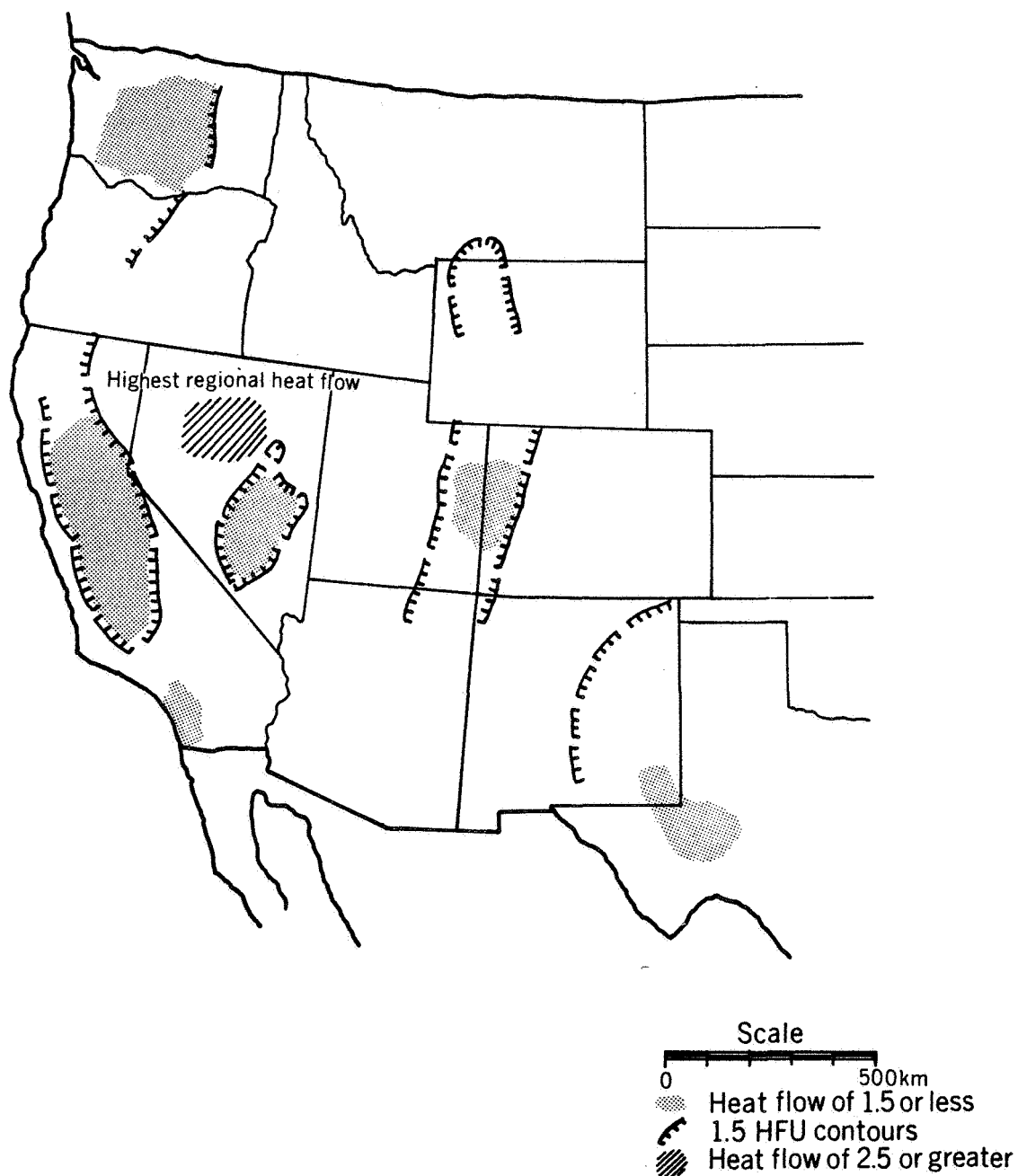
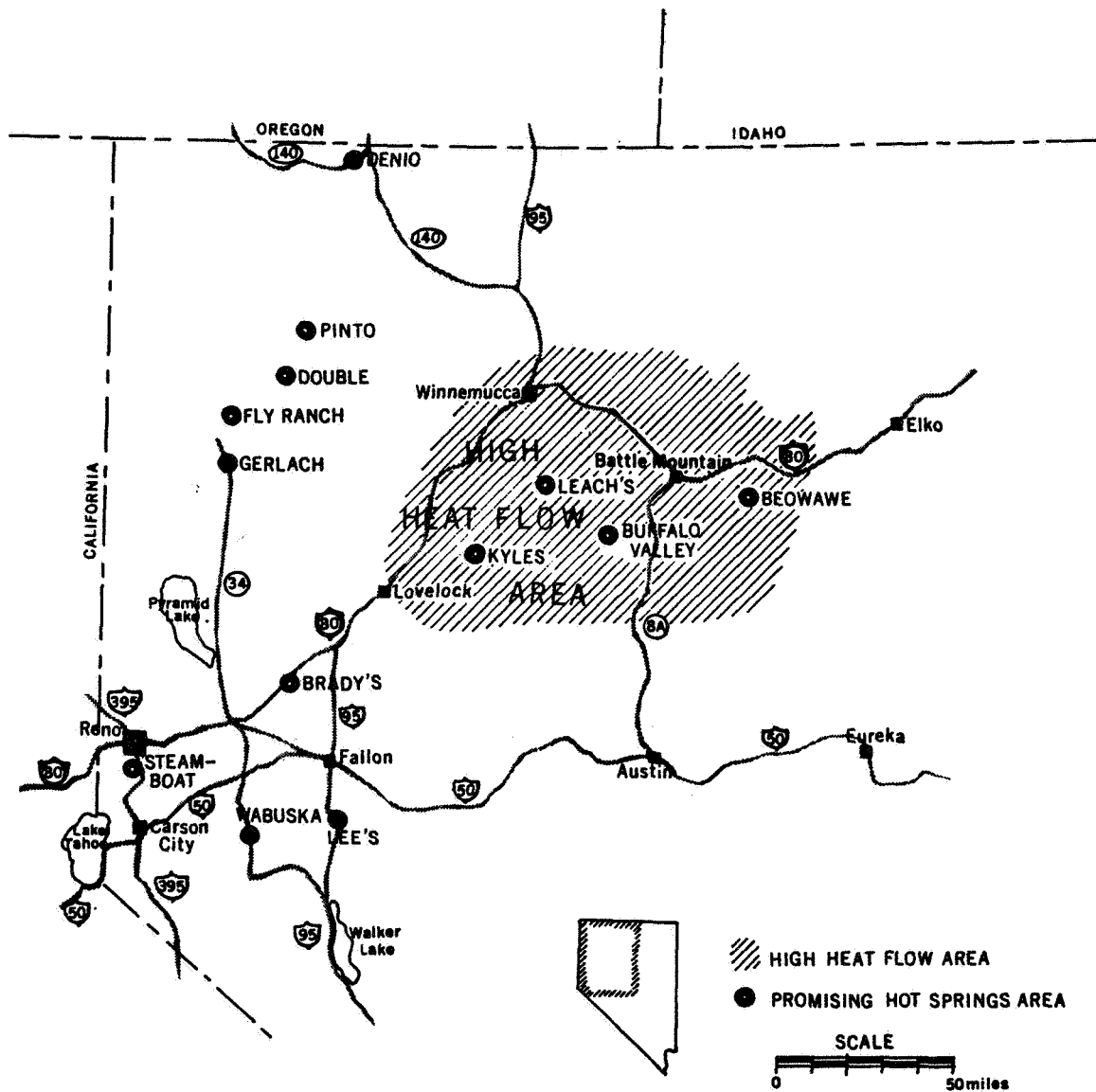


Fig. 1. Regional heat flow in the western U.S. (Ref. 1). The stippled areas have heat flows estimated less than $1.5 \mu\text{cal-cm}^{-1}\text{-sec}^{-1}$ (HFU), while in the dashed area, the "Battle Mountain High" heat flow probably exceeds 2.5 HFU. Hachured lines indicate the fairly well-defined position of the 1.5-HFU contour.



Hot Springs in Northwestern Nevada

XBL 735 676

Fig. 2. Location map, northwestern Nevada, showing prominent thermal spring areas within and outside of the Battle Mountain High heat flow region

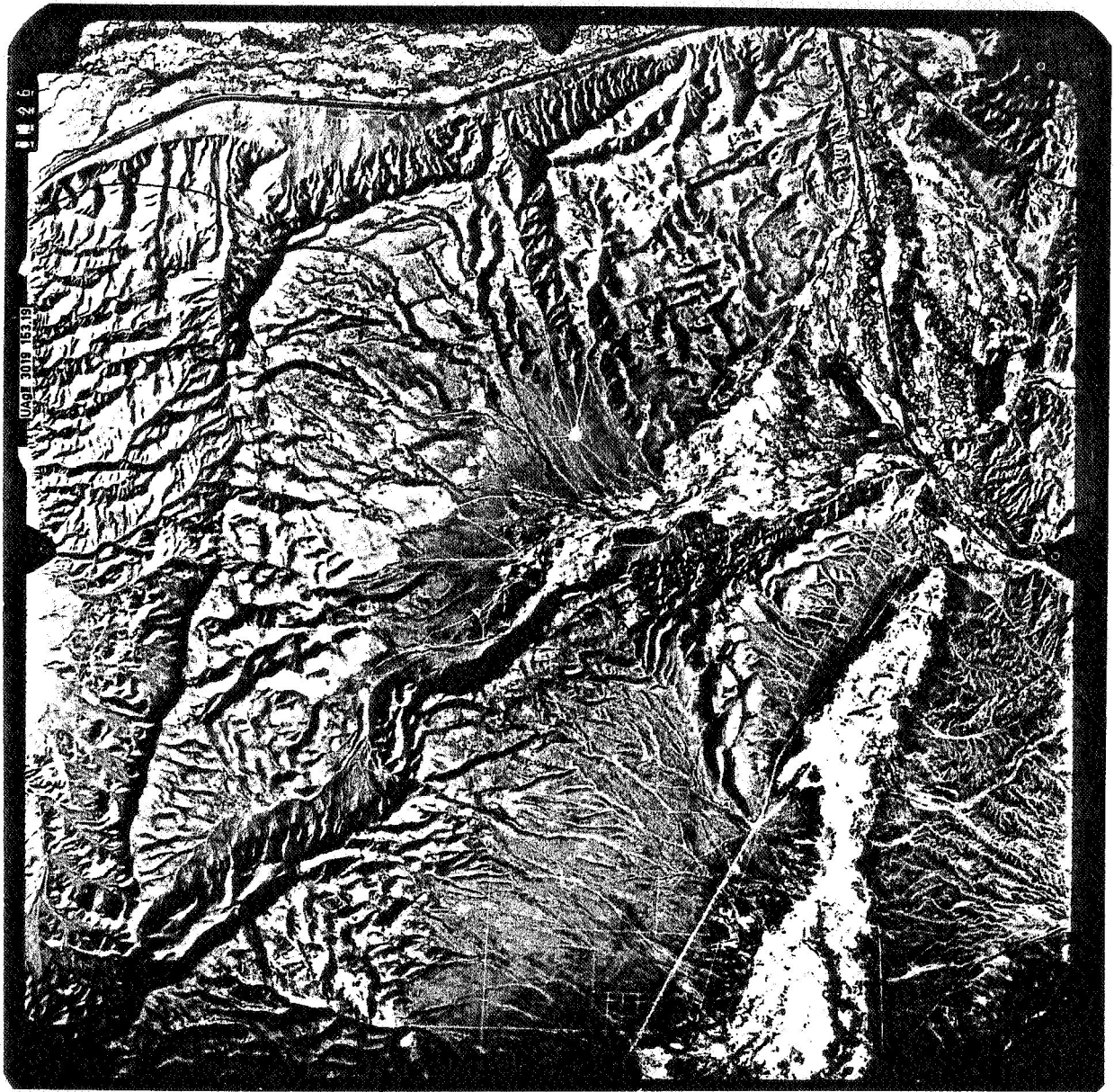


Fig. 3. Vertical aerial photograph of Whirlwind Valley region, Nevada, from 60,000 ft above surface, showing the association of geothermal area (center) near intersection of ENE-trending Malpais escarpment and NNW-trending zone of en-echelon faults. Width of field: approximately 27 km.

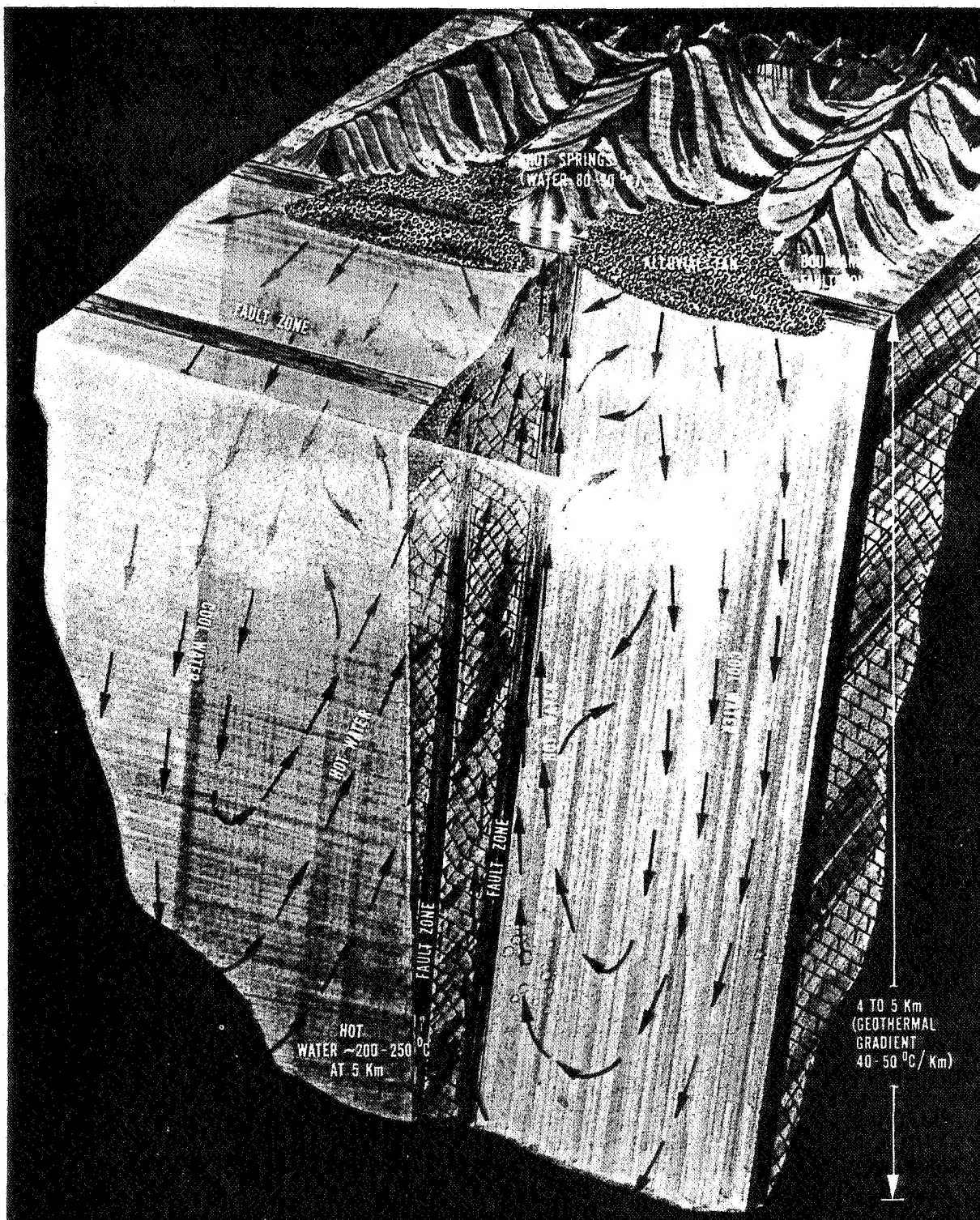


Fig. 4. Schematic cutaway diagram of a geothermal system within a permeable fault zone. Meteoric water enters the fault zone where it intersects near-surface aquifers. Some of the water percolates downward to regions where temperatures reach 150 to 200°C, is heated and rises on the upward limb of a convection cell. Hot springs occur where the cell intersects the surface.

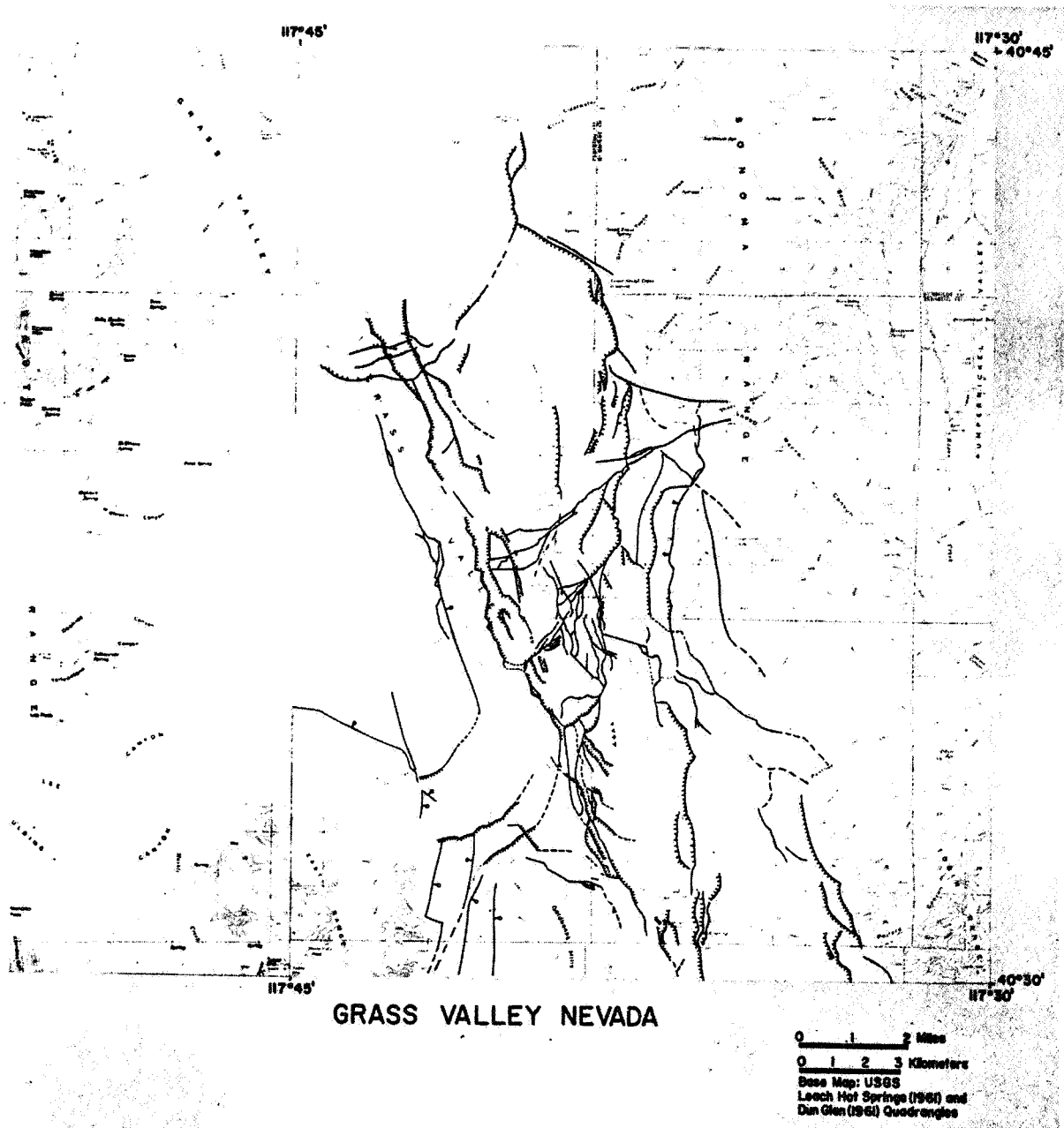


Fig. 5. Fault map of the Leach Hot Springs area. Hachured lines indicate down-faulted sides of scarplets; ball symbol indicates down-thrown side of other faults.

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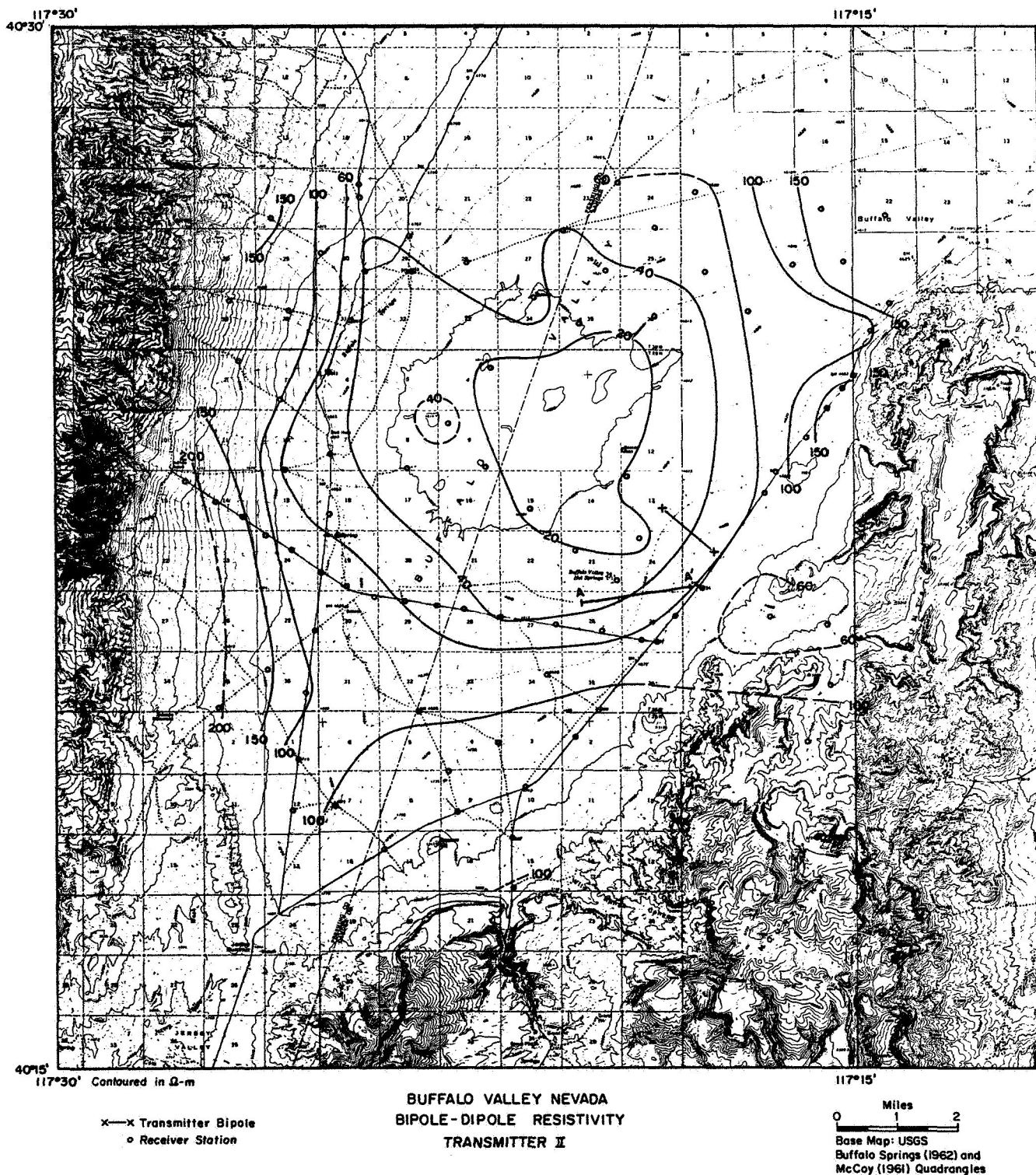


Fig. 6. Apparent resistivity pattern from a bipole-dipole reconnaissance of Buffalo Valley. Current dipole location indicated by heavy line x-x.

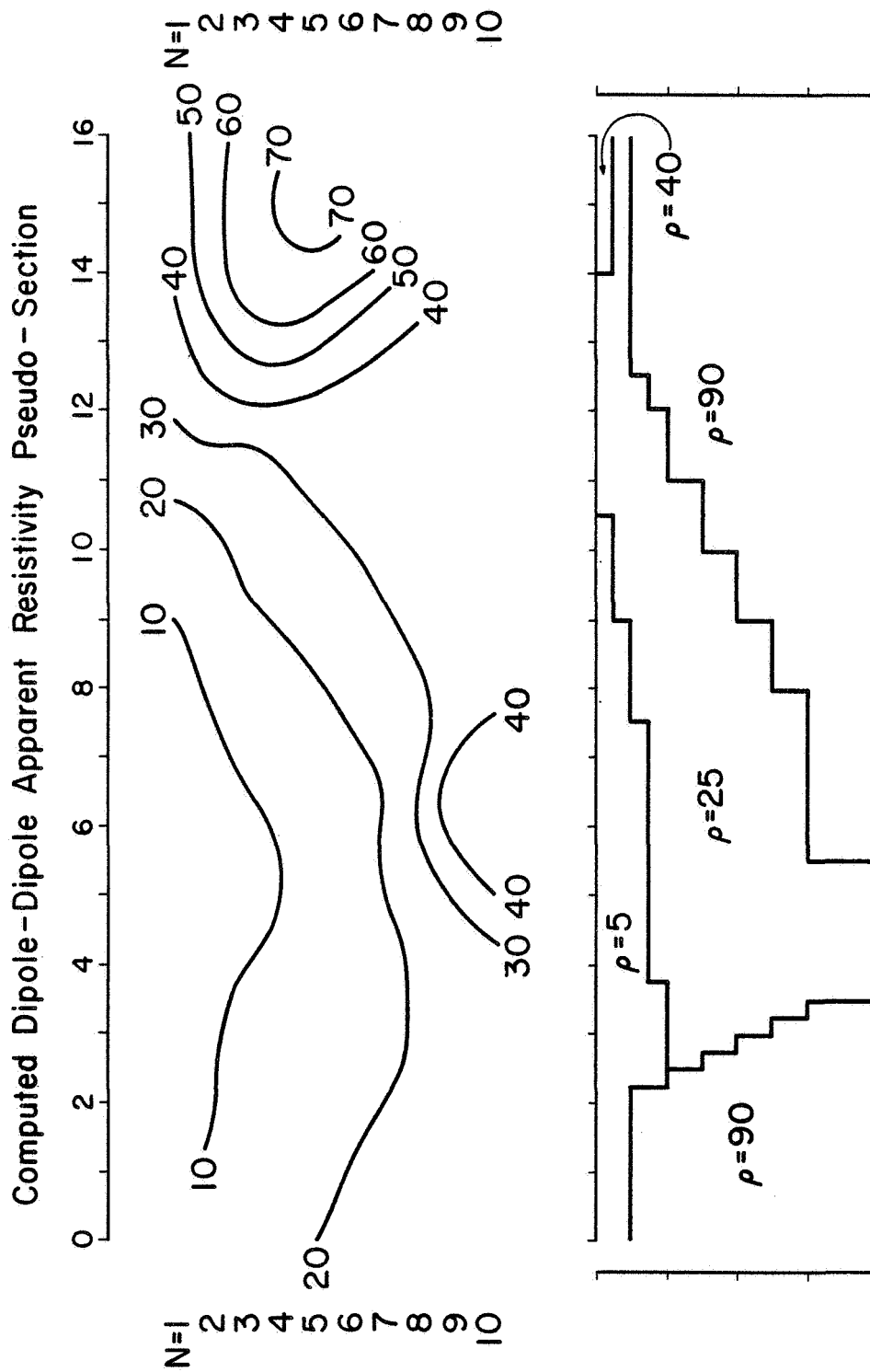


Fig. 7. (upper) Apparent resistivity pseudosection along a profile crossing Buffalo Valley; horizontal distances in km. N -values indicate number of voltage-measurement stepouts from the current dipole, apparent resistivities in ohm-meters. (lower) Computer-generated model based on the pseudosection.

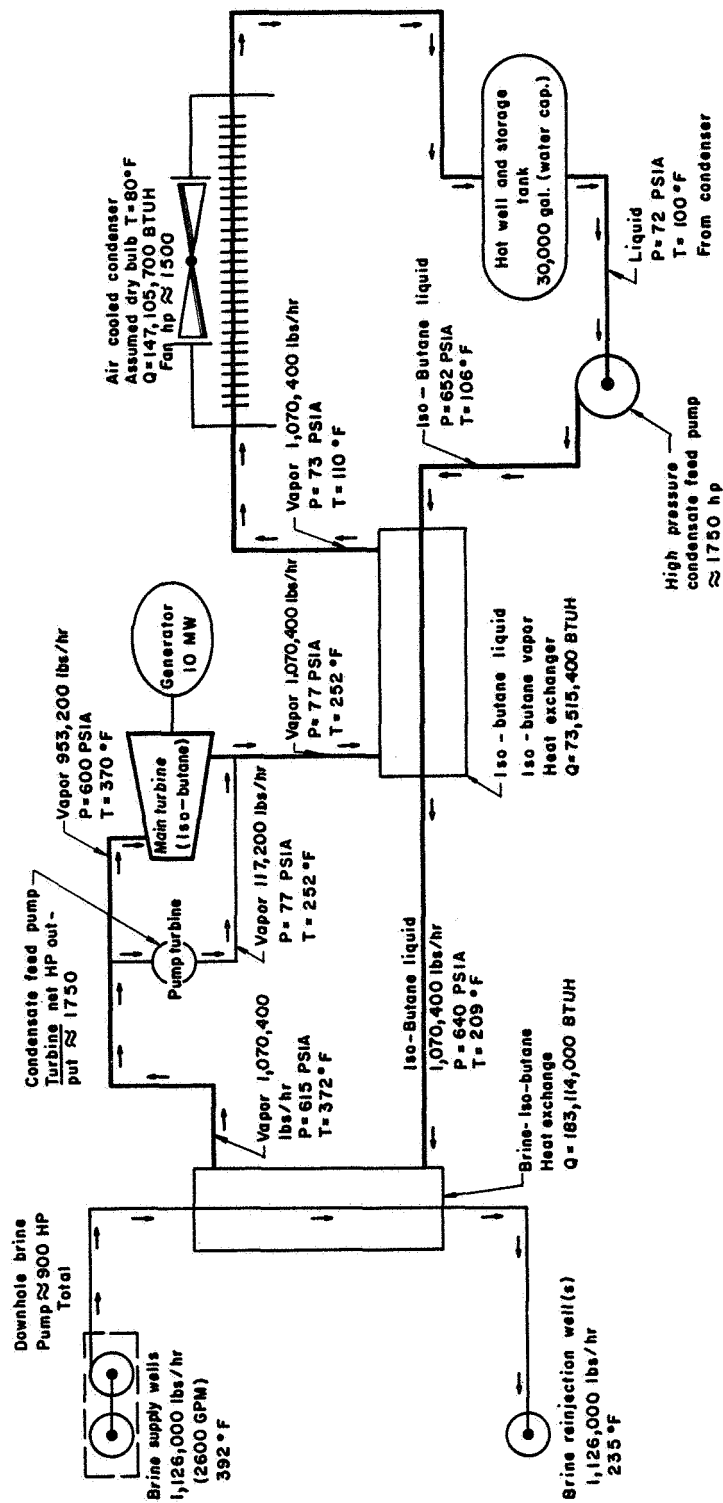


Fig. 8. Simplified flow schematic of 10-MW pilot plant brine and isobutane systems

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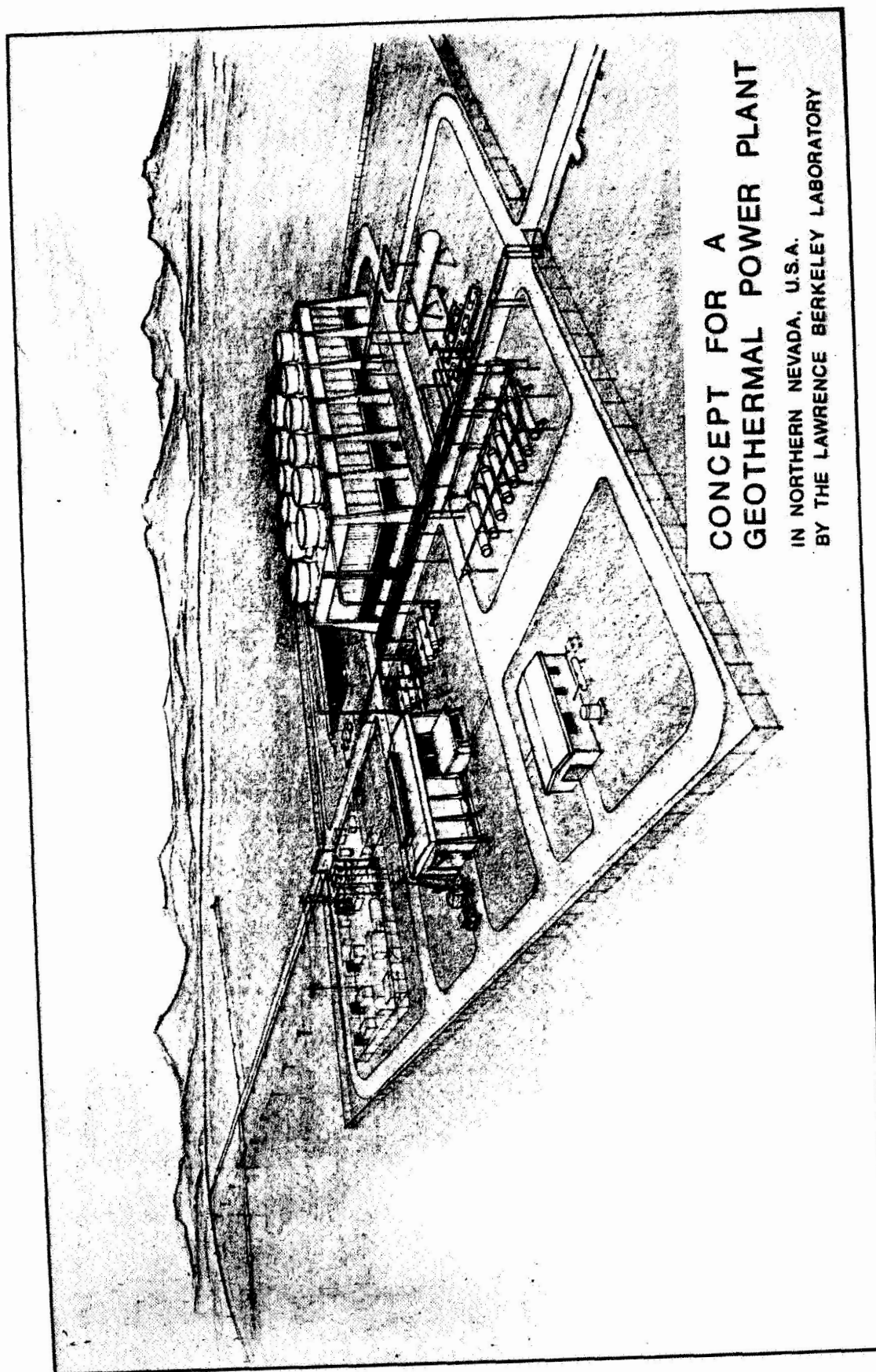
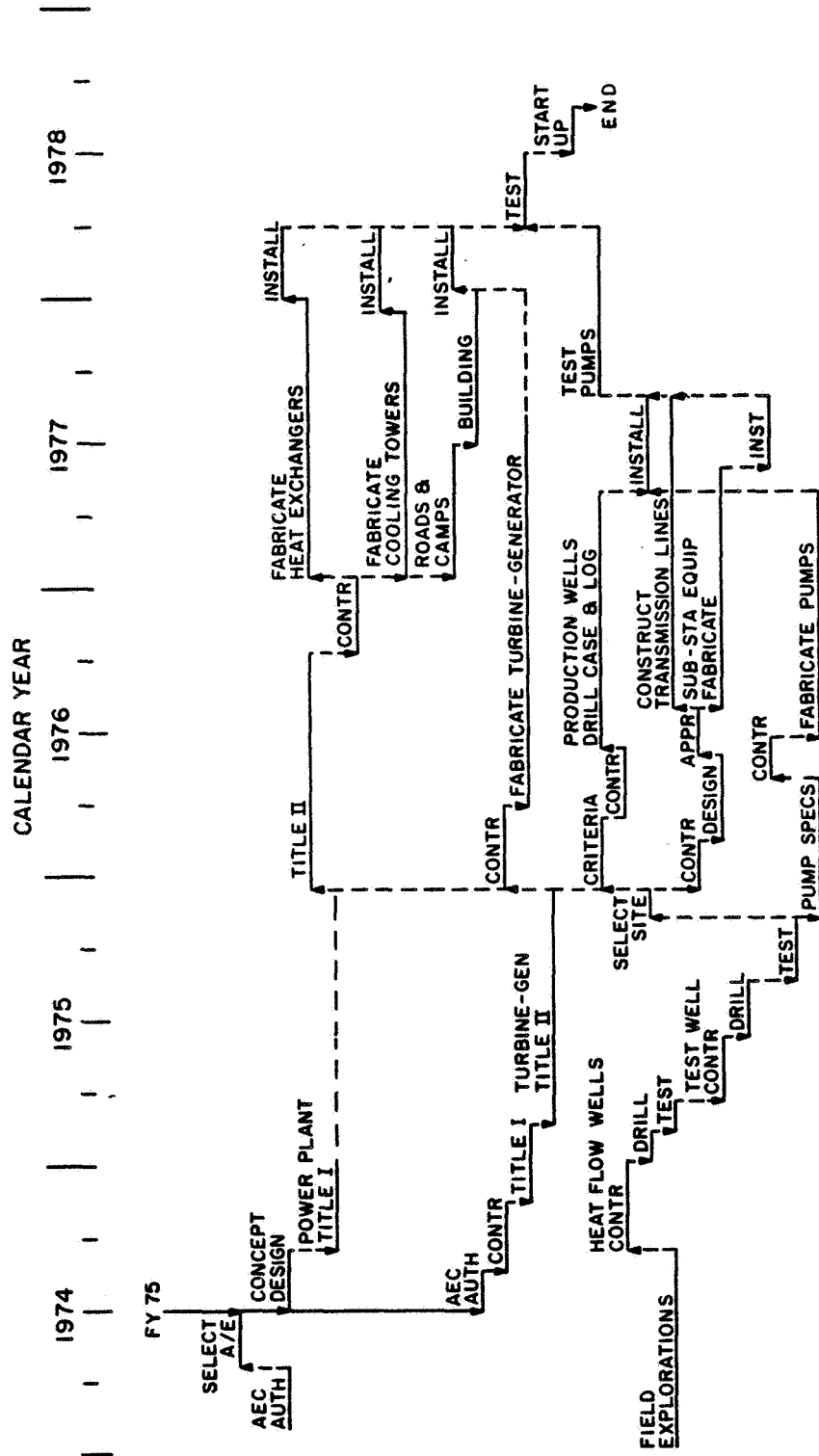


Fig. 9. Pictorial of 10-MW pilot plant

LBL
 GEOTHERMAL FIELD EXPERIMENTAL PLANT
 COST ESTIMATE
 SUMMARY

<u>Item</u>	<u>K\$</u>
Brine Distribution	4 50
Isobutane System	2 , 7 5 0
Turbine/Generator	1 , 4 8 5
Cooling Tower	1 , 9 7 0
Electrical Equipment	7 8 5
General Facilities	3 3 5
Production/Reinjection Wells	3 , 9 7 5
Engineering	<u>1 , 8 2 5</u>
Subtotal	13 , 5 7 5
Escalation	4 , 8 8 0
Contingency	<u>4 , 0 7 5</u>
TOTAL	K\$ 22 , 5 3 0

Fig. 10. Cost estimate summary for 10-MW pilot plant including production and reinjection wells



GEOTHERMAL POWER PLANT - LBL

Fig. 11. 10-MW pilot plant schedule

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THE TOTAL FLOW CONCEPT FOR GEOTHERMAL
ENERGY CONVERSION

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A geothermal development project has been initiated at the Lawrence Livermore Laboratory (LLL) to emphasize development of methods for recovery and conversion of the energy in geothermal deposits of hot brines. Temperatures of these waters vary from 150°C to more than 300°C with dissolved solids content ranging from less than 0.1% to over 25% by weight. Of particular interest are the deposits of high-temperature/high-salinity brines, as well as less saline brines, known to occur in the Salton Trough of California. Development of this resource will depend on resolution of the technical problems of brine handling, scale and precipitation control, and corrosion/erosion resistant systems for efficient conversion of thermal to electrical energy. Research experience to date has shown these problems to be severe. Hence, the LLL program emphasizes development of an entirely different approach called the Total Flow concept. This, in principle, consists of passing the total hot wellhead brine-steam mixture directly through a mixed-phase expander to drive an electrical alternator. The purpose of this paper is to define the basic thermodynamics of this concept, expander requirements, and overall system characteristics. The LLL program plans for development of a Total Flow System will be discussed along with comments on current laboratory and field activities.

It is generally accepted that the water-dominated geothermal resources, if developed, could produce a significant supply of clean, low-cost energy. Temperatures of these waters vary from 150°C to over 300°C with dissolved solids content ranging from less than 0.1% to over 25%, by weight.

Of particular interest are the deposits known to exist in the Salton Trough of California. Estimates of the recoverable energy from this region range from about 60,000 to over 10 million megawatt-years. This variation is primarily due to lack of data on the magnitude and distribution of the stored thermal energy, and to uncertainties regarding technological prospects for economic recovery and conversion of the energy from the high saline waters. The current interest in conversion machines and systems designed uniquely for these resources is stimulated mainly because hot water resources are abundant, economic conditions encourage development of machines with highest efficiencies to minimize the number of wells per unit of electrical output, and the

range of chemical conditions encountered may require development of special systems, each tailored to specific resources and locations.

Development of the high saline waters, in particular, will depend on resolution of the technical problems of brine management, scale and precipitation control, and corrosion/erosion resistant systems for efficient, economic energy conversion systems. Solution of these problems coupled with a need to better understand the mechanisms governing reservoir lifetimes and productive capacities will require a broad interdisciplinary approach.

Before a commitment to commercial production can be made, a goal oriented research and development program is required to reduce the technological risks to an acceptable level. To accomplish this, a geothermal development program has been initiated by the AEC at the Lawrence Livermore Laboratory (LLL) to emphasize development of methods for recovery and conversion of the energy in the high temperature/high salinity brines. Research experience to date on systems operating from these brines has shown the problems to be severe. Hence, the LLL program emphasizes an entirely different approach called the Total Flow Concept for energy conversion. This, in principle, consists of passing the total hot wellhead brine-steam mixture directly through a mixed phase expander to drive an electrical generator. Figure 1 shows a comparison of this process with the Flashed Steam System on the Temperature-Entropy plane. The Total Flow process involves the expansion of the wellhead product from state point 1 to the exhaust pressure at 2. This is thermodynamically the simplest, and provides an upper bound on cycle efficiency. Regardless of the number of separation stages used in the Flashed Steam System, there will always be some useful energy discarded with the separated brine, e.g., the path A-B.

A detailed analysis of these systems operating from brines of different temperatures has been completed. The results (Figure 2) show that about a 60% increase in power output can be achieved with the Total Flow System if it can be made to function with a 70% engine, or expander, efficiency. This increase, of course, translates directly into a corresponding decrease in the number of required production wells and a reduction in capital investment.

In order to gain this advantage, however, it is necessary to extract the maximum available energy from the wellhead product. Figure 3 illustrates the basic problem. For the particular case shown ($p_1 = 360$ psia, $x_1 = 19\%$, and expansion to 3.5-inch Hg (120° F) condenser pressure) which is typical of high temperature geothermal wells, it is shown that 2/3 of the available energy is obtained by expansion from about 50 psia down to the sink condition. Hence, any Total Flow System expander must be capable of economic operation over the entire pressure range in order to produce the performance depicted in Figure 2. This means that expanders with limited expansion ratios (such as positive displacement devices) must be multiply staged to recover the available energy. Since the fluid specific volumes, for the example shown, increase from about 0.3 ft³/lb. to about 70 ft³/lb., the physical size of the low pressure stages of positive displacement devices increase accordingly, leading to enormous machines, and possibly, high costs. Consequently, development of single stage expansion devices and/or hybrid systems will likely be necessary to gain the full benefit of the Total Flow process. For some applications the latter, for example, may consist of a Total Flow device as a topping stage with exhaust to a Flashed Steam System.

Development of any conversion system for use with a high saline brine is complicated by the presence of as much as 26% dissolved solids. Precipitation of silica and other solids can cause rapid formation of scale on components and outlet piping. Consequently, a system must be designed to either allow continuous removal of scale, or precipitation and deposition control during operation. Coupled with this are problems of corrosion and erosion of materials. While materials technology advances have produced possible solutions, field experience is lacking. Field testing of candidate materials in actual brines under operating conditions must precede final system design. Hence, a complete system approach to development of the Total Flow concept is necessary, and must involve elements of earth sciences, brine chemistry, materials technology, conversion and system engineering.

The LLL geothermal program is directed toward applying and extending these technologies where necessary with emphasis on development of the Total Flow concept for recovery and conversion of the energy in the high saline brines. The key technical issues to be resolved are illustrated in Table 1. Initially, the major program emphasis will be on solutions of the brine chemistry problems and development and testing of expander concepts for energy.

Because of the advantages of full expansion of the wellhead product as shown by Figure 3, it appears that the impulse turbine may emerge as the prime candidate. It is simple, contains one moving part, the technology is already well known, and offers design flexibility. Most importantly, designs utilizing tangential, radial, or axial flow can be used to accommodate a wide range of operating conditions. These machines can be designed to be sufficiently compact to accommodate complete wellhead fluid expansion.

The important feature of the impulse turbine is that the expansion takes place in a converging-diverging nozzle to convert fluid enthalpy to kinetic energy in the form of high velocity jets. The momentum of these jets is then transferred to the impulse wheel which operates at the condenser temperature. Hence, the entire pressure drop takes place in a single component, fixed in space, which offers opportunities for scale control and brine treatment by techniques such as keeping the nozzle walls hot, periodic flexing, chemical treatment, boundary layer control, etc. One concept, among others, under development is shown in Figure 4, which illustrates a tangential flow device currently being designed for test.

It is well recognized that the major technical problems with such devices are the design of efficient nozzles and development of turbine blading to accommodate the mixed-phase flow. Analytical investigations are in progress and indicate, thus far, that efficient transfer of the momentum of the liquid phase is one of the major design tasks. However, the simplifying assumptions inherent in these early calculations limit their value as a precise design tool. Hence, the development of efficient two-phase conversion machinery will require emphasis on experimental techniques.

A geothermal test facility has been constructed at LLL for performance testing of candidate turbines, and to provide a means of test and development of turbine components such as nozzles and blading. This facility consists of a

boiler capable of producing about 1.5 lb/sec of water at 1000 psia and 550°F. By flashing, a wide range of typical wellhead thermodynamic characteristics can be reproduced. The facility includes condensing equipment to allow operation at backpressures down to about 3.5 inch Hg (120°F). The capability now exists for complete testing and evaluation of Total Flow machines up to about 100 kW in capacity as well as the means for fundamental investigation of the mechanics of two-phase flow. The system is shown schematically in Figure 5 which shows a cutaway of the test chambers and control room.

In conjunction with this, field testing on a high saline well in the Imperial Valley has begun. This currently is limited to flowing brine through nozzles and over-simulated turbine blades for preliminary material screening and early evaluation of brine handling and scaling problems. Since the brines cannot be adequately simulated in the laboratory under dynamic flowing conditions, it is necessary to carry out brine analyses and treatment experiments in the field, on a flowing well. Preliminary results indicate that one material (Teflon PFA) underwent 100 hours of test without significant scaling in the nozzle or erosion of the wear plate. Additional tests of other materials are being prepared, and field systems for instrumentation and brine analysis are being designed for use this fiscal year.

The overall LLL program goal is the development of complete Total Flow systems for recovery and conversion of the energy in hot water deposits with emphasis on the high salinity resource. Resolution of the key technical issues is planned for early FY 77. Laboratory and field testing of small scale brine tolerant turbines is scheduled for completion by the end of FY 76. Culmination of this development effort should lead to a baseline design for a brine tolerant Total Flow conversion system which will include evaluation of commercial configurations as well as specially designed units. During this time, plans for site selection and development (including drilling) will be made so that construction of a complete demonstration system of about 10 MW capacity can be initiated in FY 77. Depending on the results of the research efforts, installation and operation of the 10-MW experimental power plant is planned for FY 79.

This experimental plant is intended to contain all the necessary elements, including methods for control, fluid handling, reinjection, condensing and cooling, and fully instrumented for determining operation characteristics. It is intended that the system be experimental in nature in order to provide a flexible test facility for evaluation of candidate energy conversion systems. Early involvement of private industries with machines, techniques, or systems for application to the Total Flow process will be actively sought. Current involvement consists of coordination with those doing similar development work, development of agreements to gain access to flowing wells, and negotiations for purchase of existing conversion machines for test and evaluation on the LLL test facility prior to field testing with high saline brines.

Table I.. High-temperature high-salinity geothermal program
key technical issues

Conversion	Chemistry and materials	Resource characterization
Total flow concepts	Brine chemistry	Location and magnitude
Develop baseline design	Scaling mechanism	Geochemistry
Component tests	Precipitation	Reservoir lifetime
Small-scale turbine		Productive capacity
System design and optimization	Material selection	
Control	Corrosion	
Condensing and disposal	Erosion	
Hybrid systems	Fabrication	
Plant characterization		
Economics		

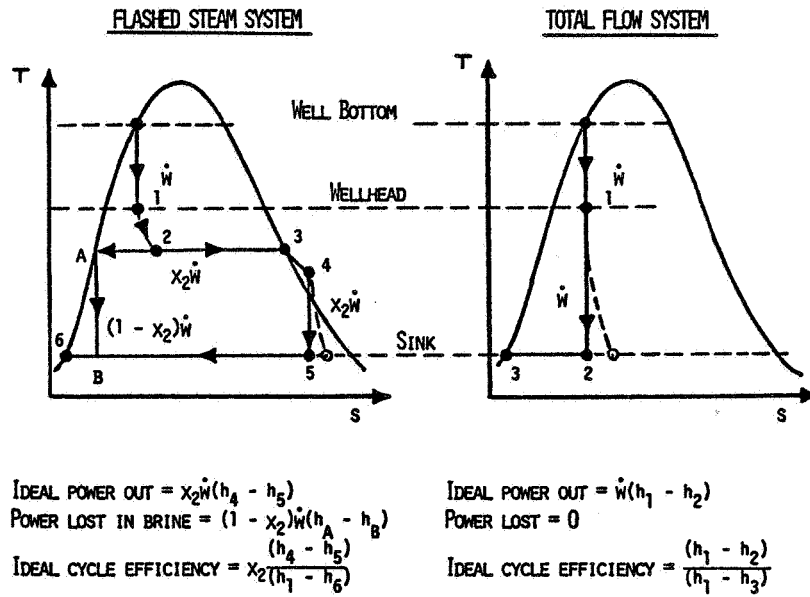


Fig. 1. Comparison of flashed steam and total flow systems

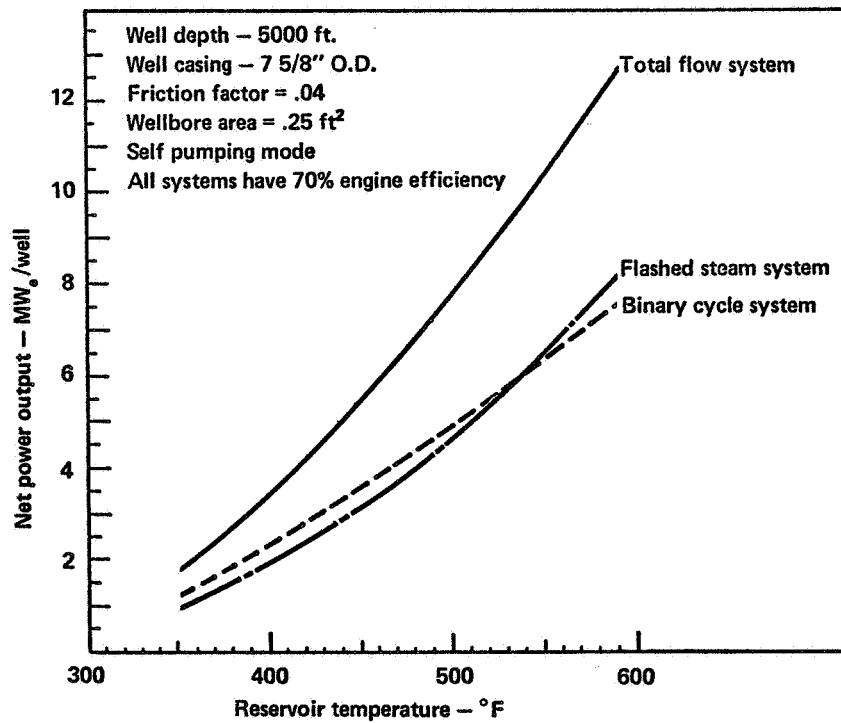


Fig. 2. Comparison of geothermal power systems

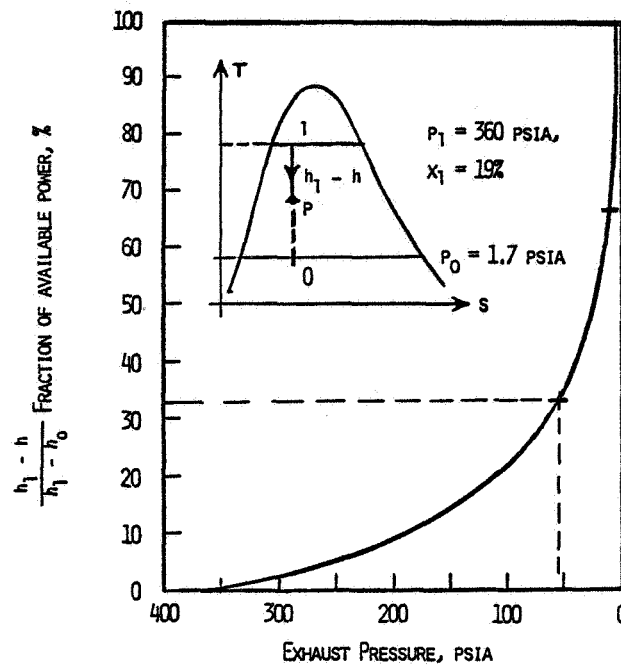


Fig. 3. Recovery of available power for an isentropic expansion of wet steam characteristic of a hot-water geothermal well

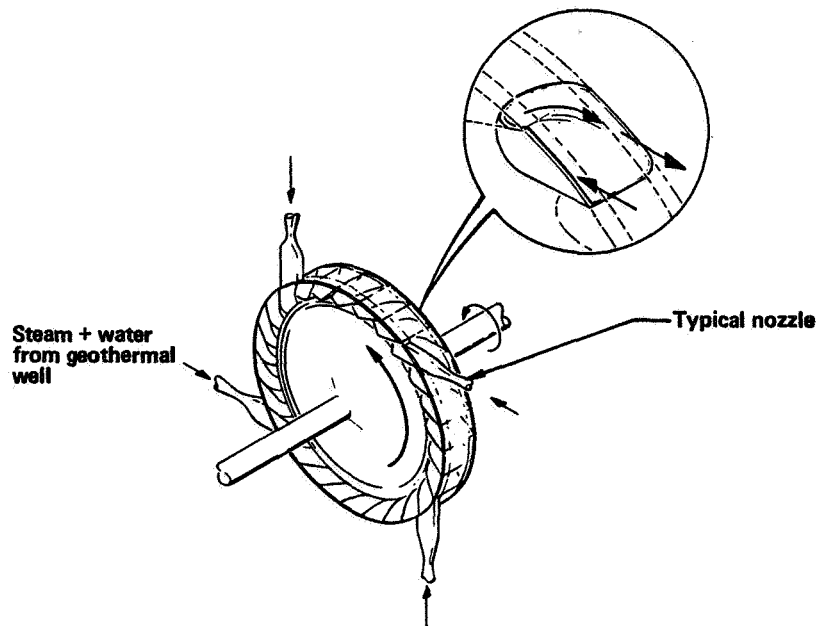


Fig. 4. Tangential flow experimental turbine for total flow geothermal application

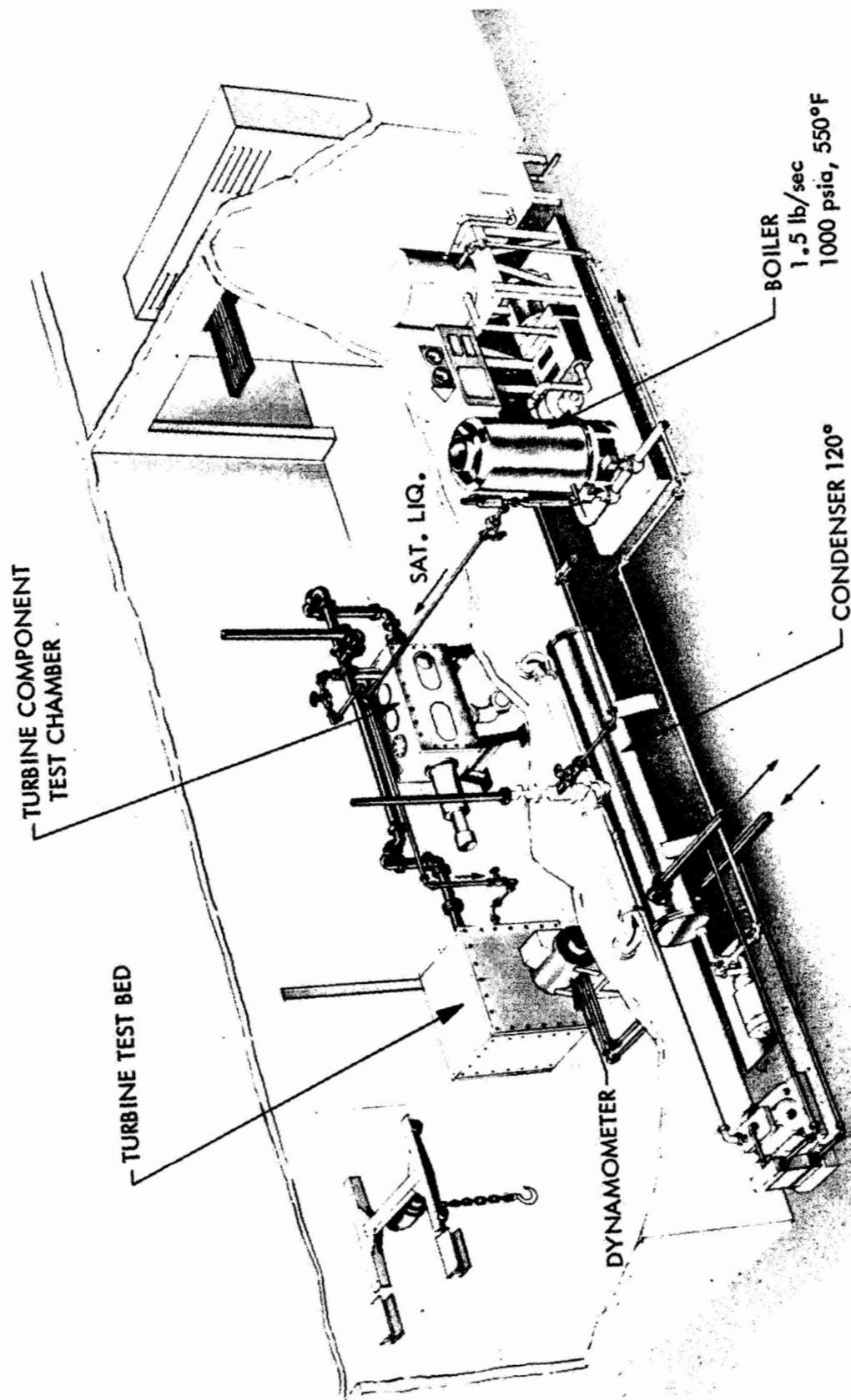


Fig. 5. Geothermal test facility

SAN DIEGO GAS & ELECTRIC COMPANY
IMPERIAL VALLEY GEOTHERMAL ACTIVITIES:
A STATUS REPORT

Thomas C. Hinrichs
San Diego Gas & Electric Company
San Diego, California

San Diego Gas & Electric and its wholly owned subsidiary New Albion Resources Co. have been affiliated with Magma Power Company, Magma Energy Inc. and Chevron Oil Company for the last 2-1/2 years in carrying out geothermal research and development in the private lands of the Imperial Valley. The steps undertaken in the program will be reviewed and the sequence that must be considered by companies considering geothermal research and development will be emphasized. Activities at the south end of the Salton Sea and in the Heber area of Imperial Valley are leading toward development of demonstration facilities within the near future. The current status of the project will be reported.

San Diego Gas & Electric Company became interested in entering the geothermal arena in 1971. Two factors weighed heavily in making the decision. One was the realization that the availability of low cost natural gas for boiler fuel in our electric power plants was to diminish very rapidly. The other factor was that the work being carried out in the Imperial Valley by the University of California Riverside team, under the sponsorship of the United States Bureau of Reclamation was demonstrating a potential geothermal resource within an economic distance of our Company's service area. San Diego Gas & Electric serves San Diego County and a portion of southern Orange County with their electric distribution system.

San Diego Gas & Electric Company actually became involved in geothermal activities through an agreement with San Diego Gas & Electric Company's wholly owned resource subsidiary New Albion Resources Company (NARCO) and the Magma Power Company and Magma Energy Inc. The agreement provided that in return for funding drilling and testing on Magma leases in the Imperial Valley NARCO could obtain an interest in the leases.

During early 1972 drilling was carried out in several areas of the Valley to identify locations that appeared promising for development. The most promising areas were the Niland area at the south end of the Salton Sea and the Heber area south of the town of El Centro. A second well was drilled at each of these locations to confirm the initial findings and also to provide a reinjection capability for flow testing.

Flow testing at the Niland site was carried out in mid-1972 with a large wellhead separator that was loaned to us by the Union Oil Company. The test performed provided information on well deliverability, fluid characteristics and other necessary information needed to initiate design work on a test facility to determine if power generation from the resource would be feasible.

In August of 1972 the C.F. Braun Company of Alhambra, California, was contracted with to design and procure major equipment for a geothermal test facility. The facility was designed on the binary system using a single steam flash with the steam and brine from the flash tank being directed through heat exchangers, which would heat isobutane. This work was completed in early 1973. An area of uncertainty in the design was the longevity of the brine heat exchangers. The Company chose to run some small scale field tests prior to starting construction on the geothermal test facility.

During 1973 a small scale test facility was constructed and installed at the Niland site. Figure 1 illustrates the flow diagram for the 1973 test hardware. Well fluids from the producing well entered the separator at 150 psig. Steam from the top of the separator passed through the heat exchanger, and brine leaving the bottom of the separator flowed through another heat exchanger. The temperature of both the steam and the brine was approximately 370°F. The mineral content of the geothermal brine from the Niland reservoir being produced was approximately 200,000 ppm. The solids in the steam leaving the test separator were 40,000 to 80,000 ppm. In both the steam and brine exchangers heat transfer performance declined from an initial value to the design limits in approximately 100 hours of operation.

Testing continued until the fall of 1973 and a satisfactory solution for mitigating the brine and steam scaling was not developed and starting of construction of the large geothermal test facility was delayed.

In early 1974 test work was resumed to develop effective methods of separating steam from the geothermal brine and scrubbing the steam to achieve as pure a product as possible. Brine heat exchanger testing was discontinued. Figure 2 shows the flow diagram of the 1974 test apparatus. These tests, which were completed during the summer of 1974, consisted of passing steam through separators, scrubbers and heat exchangers. The goal was to determine if scrubbing the steam would eliminate the severe scaling problems.

The first phase of the testing consisted of evaluating different types of steam separators. The separator selected yields steam on the outlet with a solids content of approximately 200 ppm, thus yielding a reduction from the initial well fluid of 200,000 ppm. Figure 3 is a cutaway view of the separator showing the interior of the vessel. Both the first stage (150 psig) and the second stage (50 psig) separators are the same in configuration. Well fluid enters the separator at the port located in the bottom left side and impinges on the vessel end dome where a plate provides for protection of the vessel wall. Separator steam leaves through the upper port at the right. Brine collects at the bottom of the vessel and flows to the second stage unit through the port at the lower right of the figure.

Figure 4 illustrates the internals of the steam scrubber. Steam from the separator enters the scrubber through the lower left-hand port. The steam then flows upwards through five trays which hold pure water. The water contacting the steam scrubs entrained solids in the steam. Clean steam exits at the top and wash water continuously added to the scrubber enters at the top of the vessel and cascades to the drain at the bottom. During the 1974 test the solids in the steam leaving the scrubber were 10 ppm to 20 ppm in comparison to the 100 to 200 ppm entering the scrubbers from the separator.

Figure 5 illustrates the type of heat exchangers used during the test. The first stage heat exchanger utilized steam flowing on the outside of the tubes while the second stage utilized steam flowing through the tubes. Approximately 1,000 pounds per hour of steam for both the first and second stage flowed through the heat exchangers and was completely condensed. Distilled water was circulated in a closed loop through the heat exchanger to provide the cooling mechanism.

Figure 6 illustrates some most encouraging results by comparing the overall heat transfer coefficient versus time of operation for the 1973 and 1974 first stage tests. The 1974 test results indicate the heat exchangers will operate for 3200 hours before reaching the design conditions requiring cleanup whereas the 1973 results reached the design condition in 108 hours. Total operating time for the first stage heat exchanger during the 1974 test was 398 hours, which was sufficient to establish the trend to predict the number of hours of operating before reaching design.

Figure 7 shows similar data for the second stage steam heat exchangers. 1973 test results indicated 81 hours to reach design conditions requiring cleaning. 1974 test data indicates the second stage heat exchangers will operate 10,050 hours before reaching design conditions. Operating time for the second stage heat exchangers during the 1974 test was 587 hours.

Figure 8 illustrates the flow diagram of what we anticipate the major geothermal test facility to consist of, utilizing three stages of steam separation instead of two used during the recent small scale test work. This three stage steam flash process would not make use of the brine in the heat exchangers, but rather would flash the brine to steam in three stages and then upon recondensing the steam would be combined with the residual brine and reinjected in the injection wells. The steam would be passed through scrubbers to be further cleaned after separation and run through heat exchangers against an isobutane working fluid which would power the turbine generator. The San Diego Gas & Electric Company has contracted with the Ben Holt Company of Pasadena to do the necessary redesign work on the geothermal test facility and it is anticipated that field construction will start in early 1975.

At the Heber location, following the drilling of two wells by NARCO and Magma Energy Inc., Chevron Oil Company drilled a well on their adjacent lease. In 1973 the three companies entered into an acreage pooling agreement and are carrying out extensive testing in the Heber area with Chevron acting as operator for the parties.

Because the resource at Heber is in the moderate temperature range the fluid must be pumped to enable a sufficiently high temperature to be maintained at the surface. The process anticipated to be applicable at Heber is Magma Energy's Magmamax Power Process illustrated in Fig. 9.

Since early this year Chevron has been operating two shaft driven pumps in two wells at Heber and injecting the pumped fluid into a third well. Through this operation valuable reservoir information has been accumulated and operating experience in pumping gained.

Recently San Diego Gas & Electric Company has installed a heat exchanger test module at the site and is collecting information on heat exchanger performance. The Heber fluids are much less in salinity than the Salton Sea fluids (approximately 1/10 of the total dissolved solids) and it may be feasible that direct heat exchanger operations can be performed with the Heber fluids.

With the information obtained from the well production activity Chevron is carrying out evaluation of the reservoir. Three additional wells have been drilled in the area to gain more needed information relative to reservoir potential. An additional two months are anticipated before the heat exchanger testing is completed.

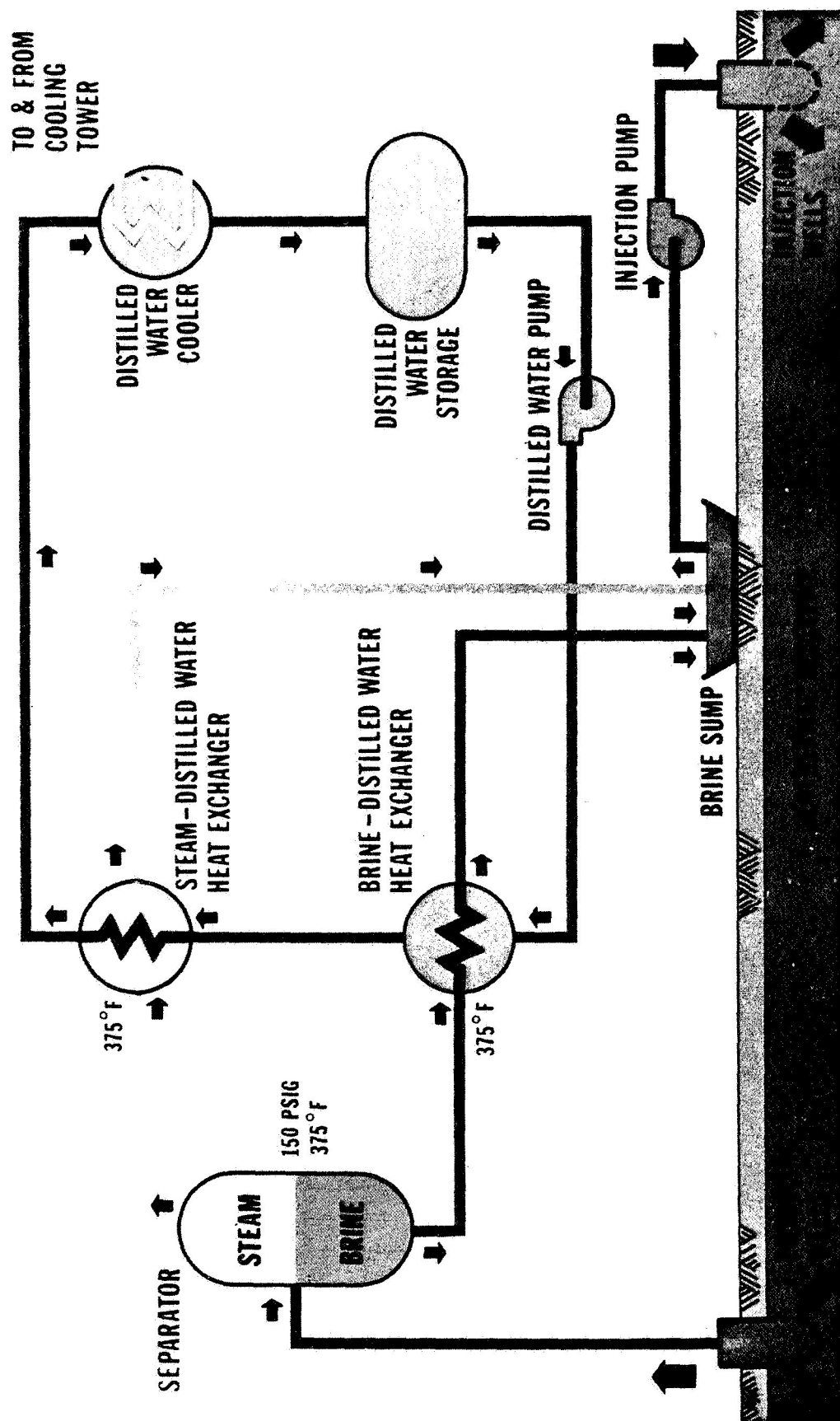


Fig. 1. 1973 geothermal field test system

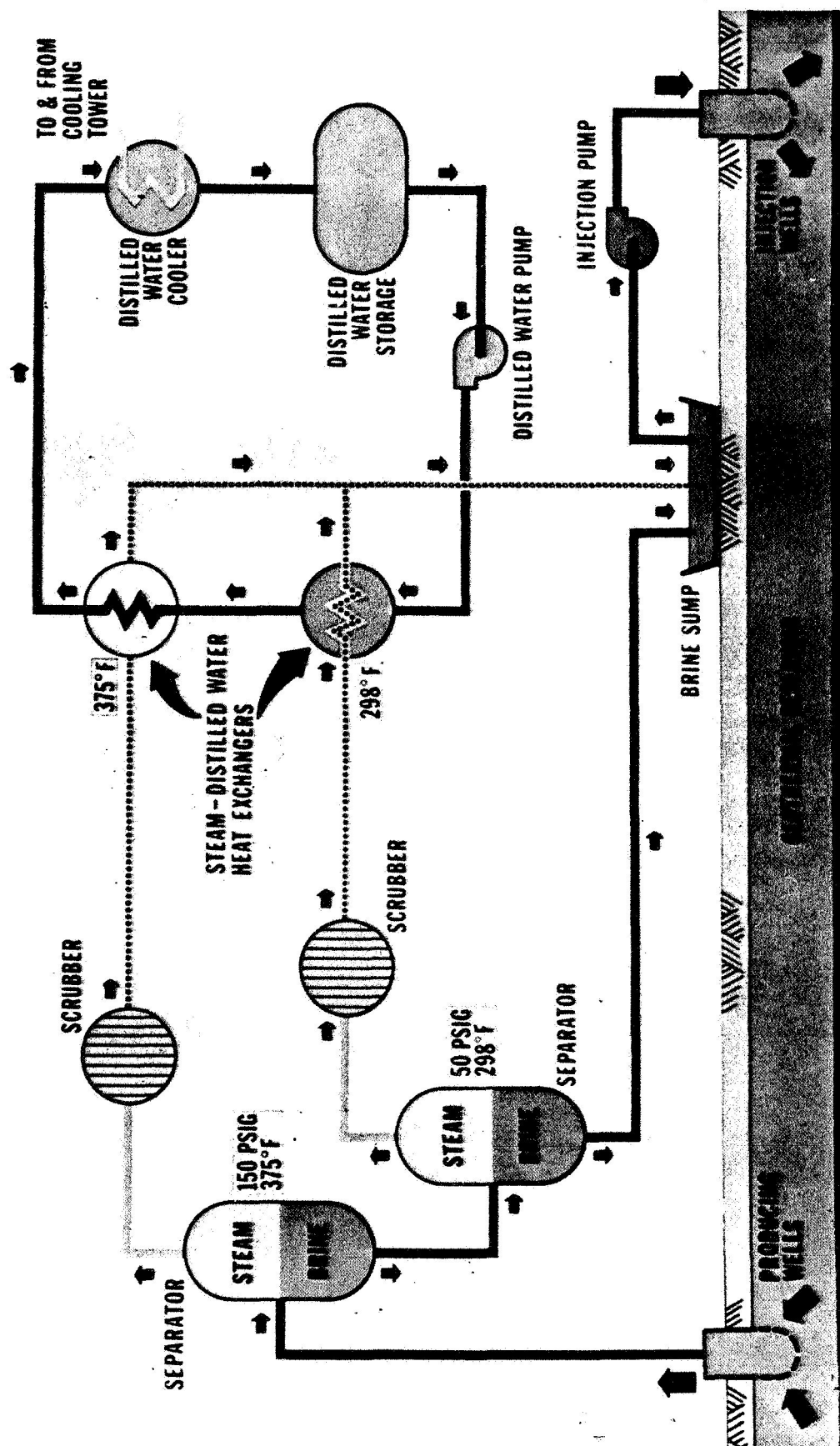


Fig. 2. 1974 geothermal field test two-stage flash system

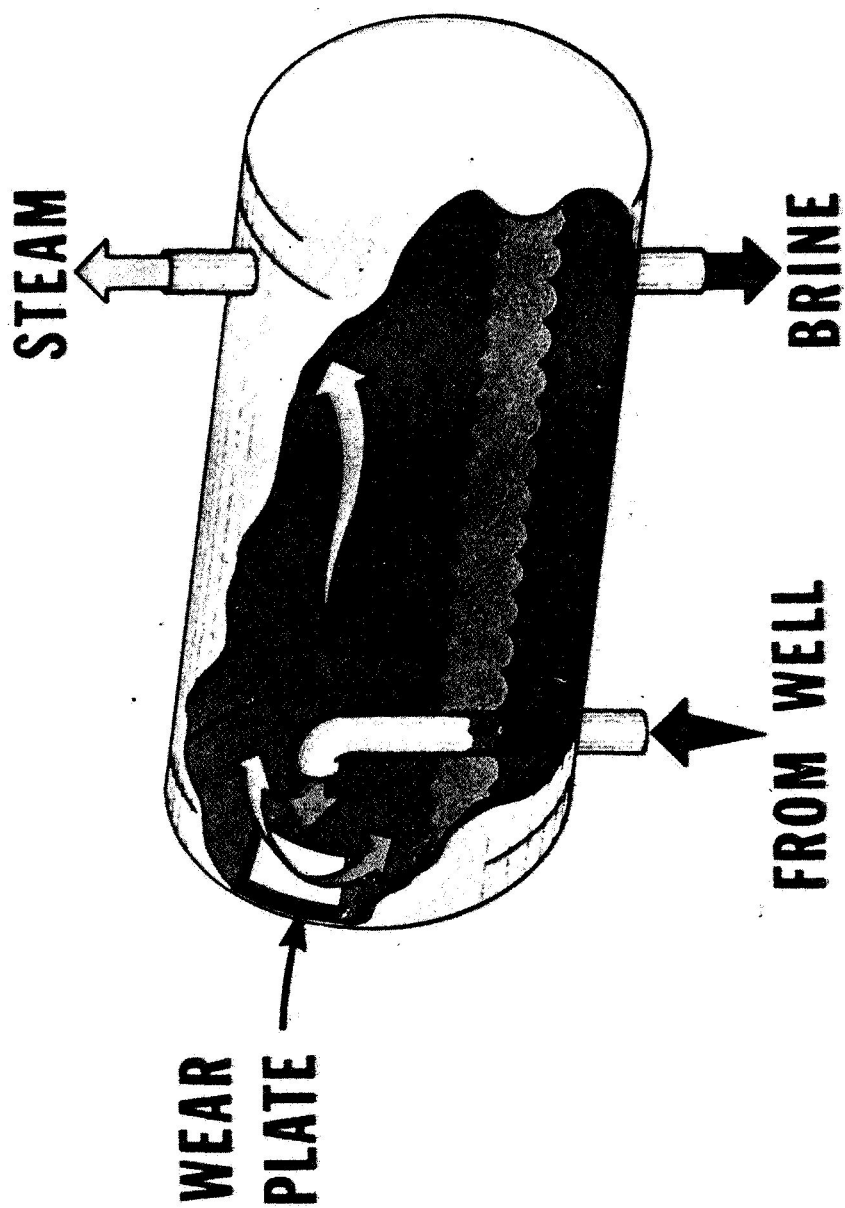


Fig. 3. C.F. Braun scale-model separator, 1974 field test

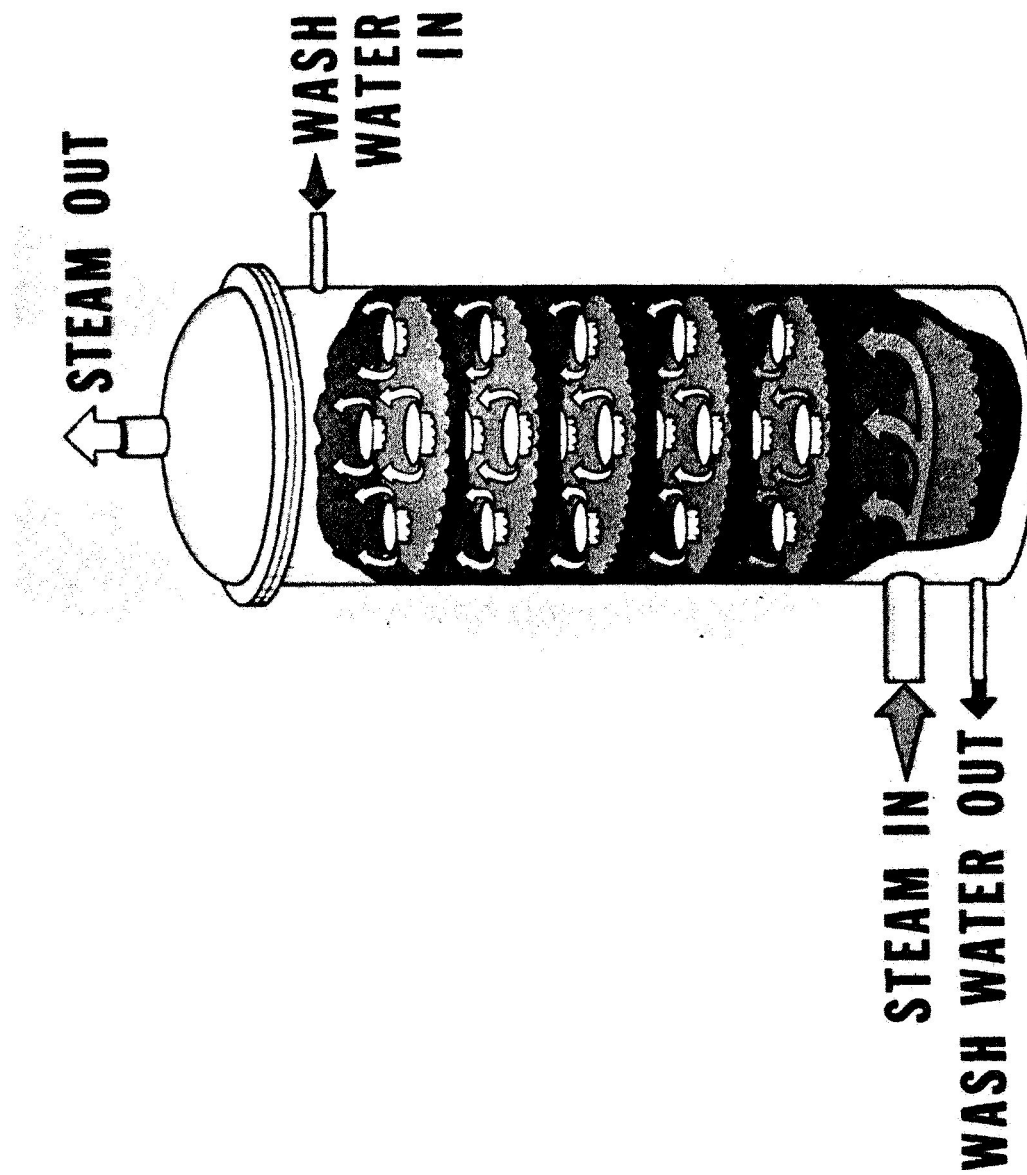


Fig. 4. Ben Holt steam scrubber, 1974 field test

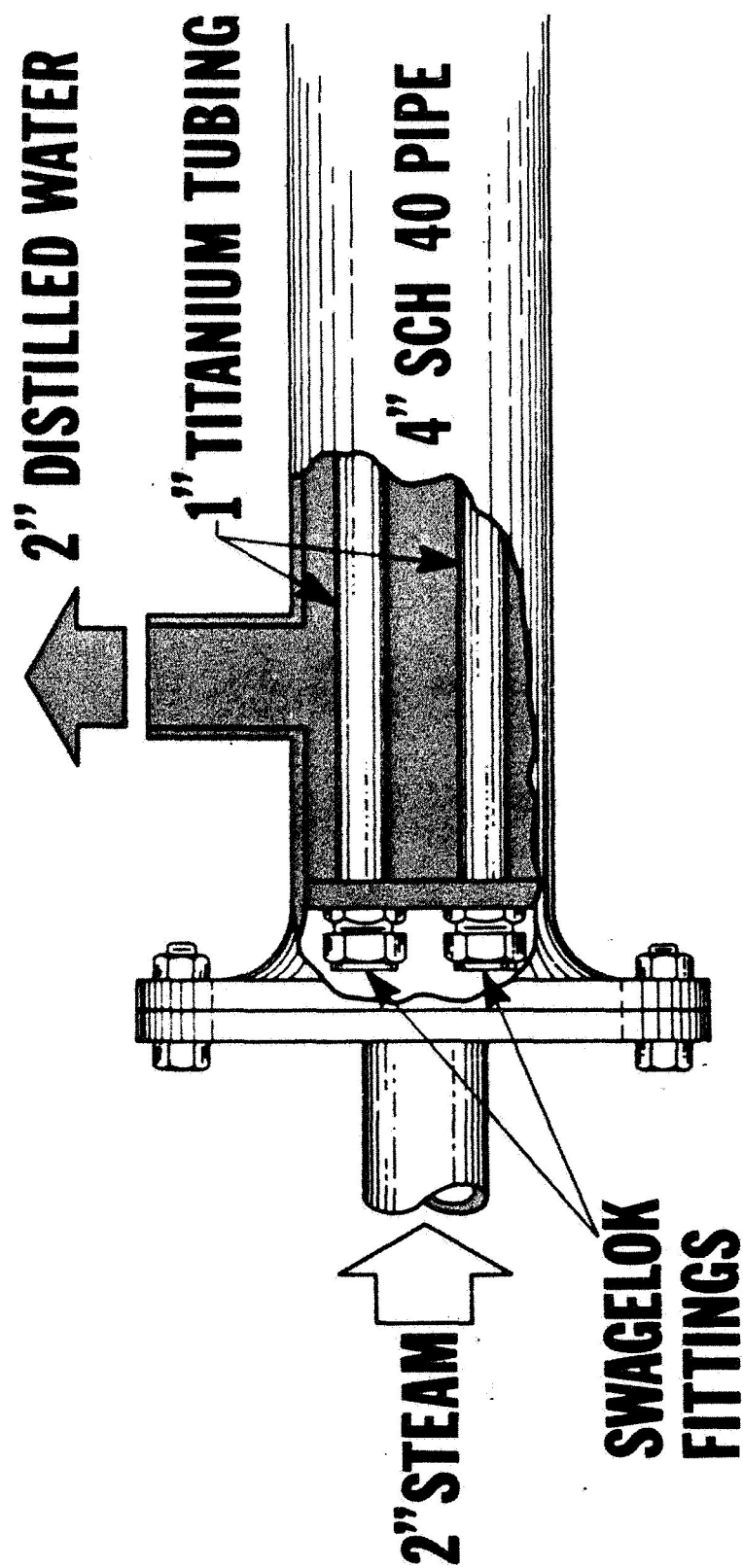


Fig. 5. Heat exchanger

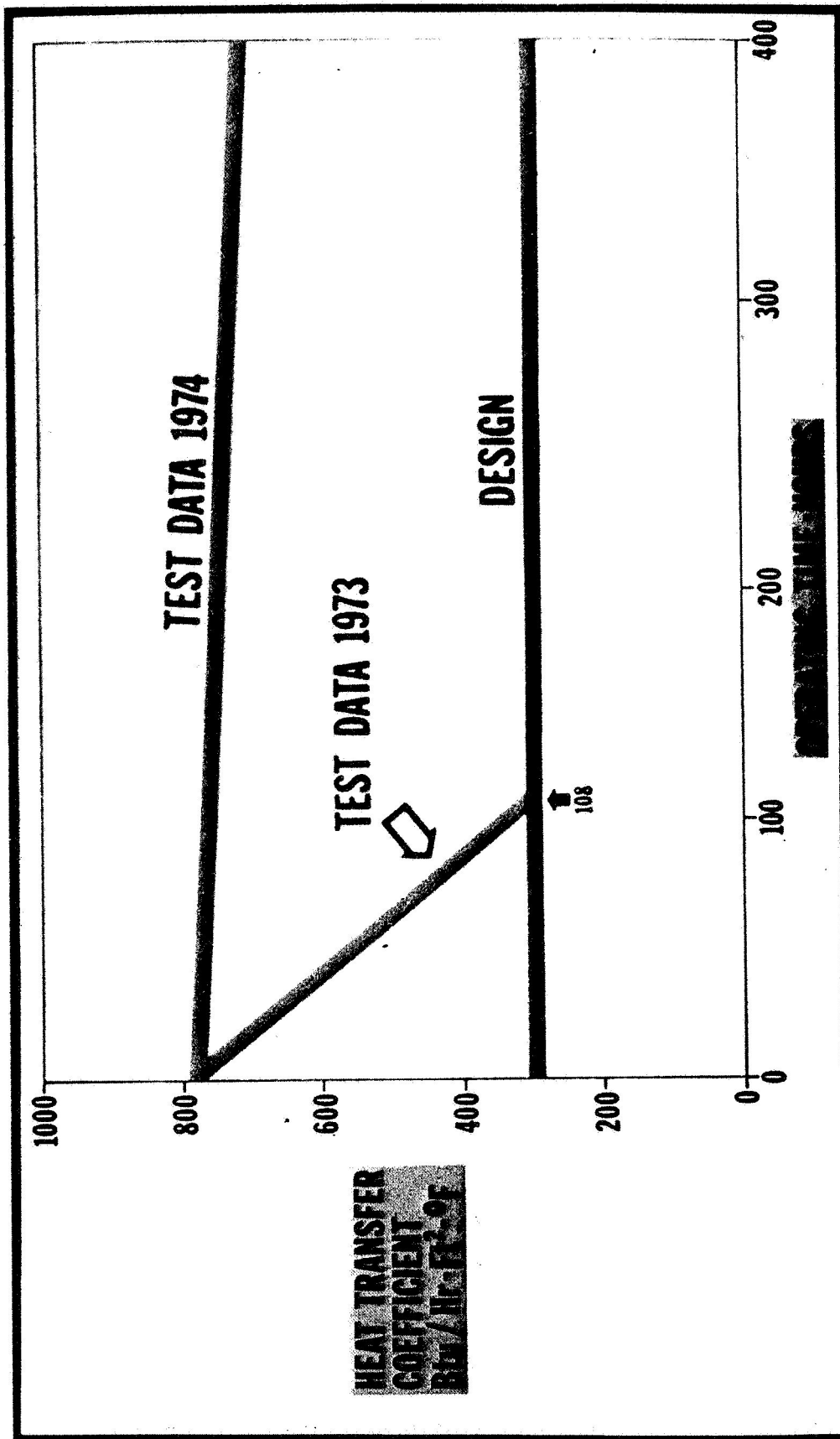


Fig. 6. First stage heat exchanger tests

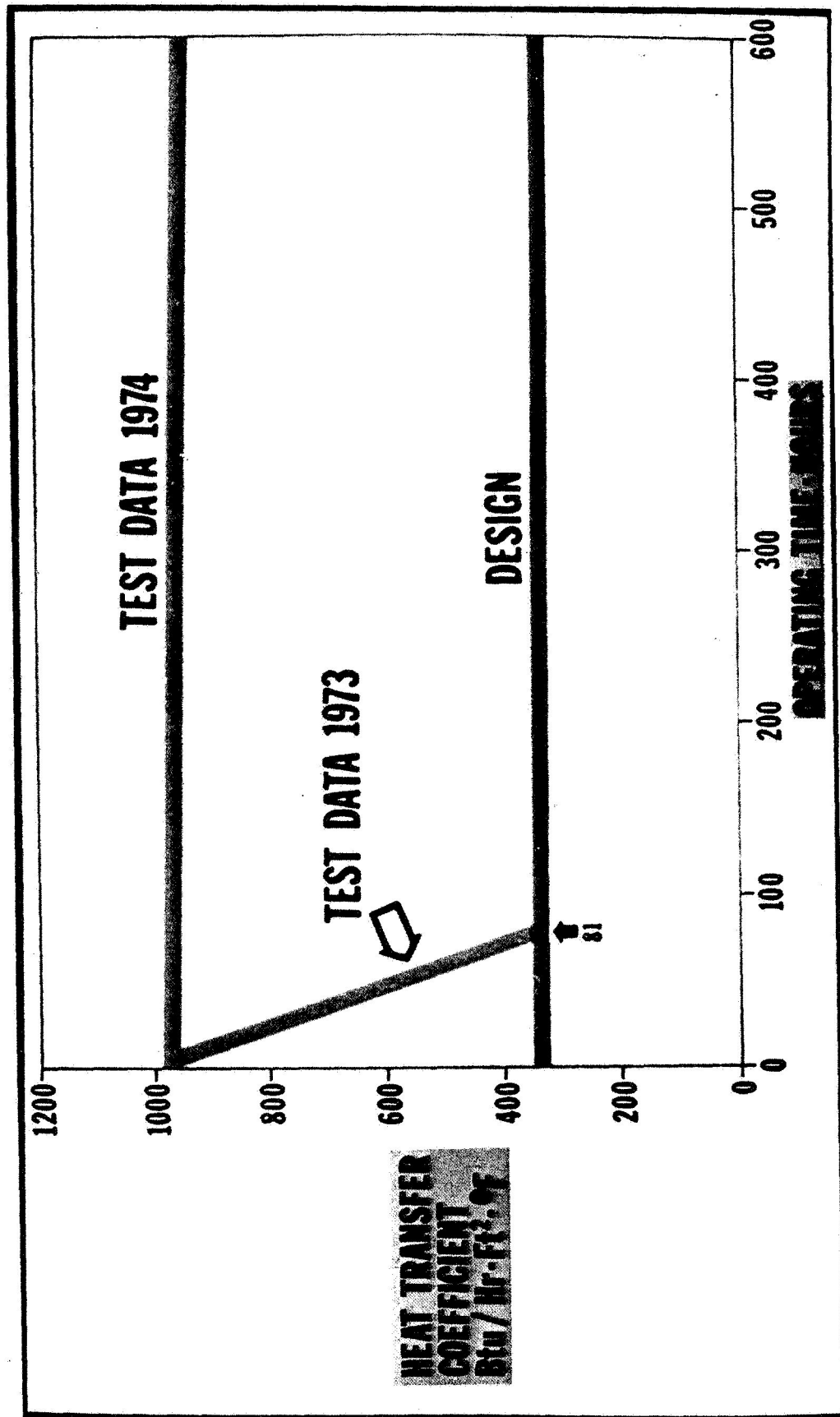


Fig. 7. Second stage heat exchanger tests

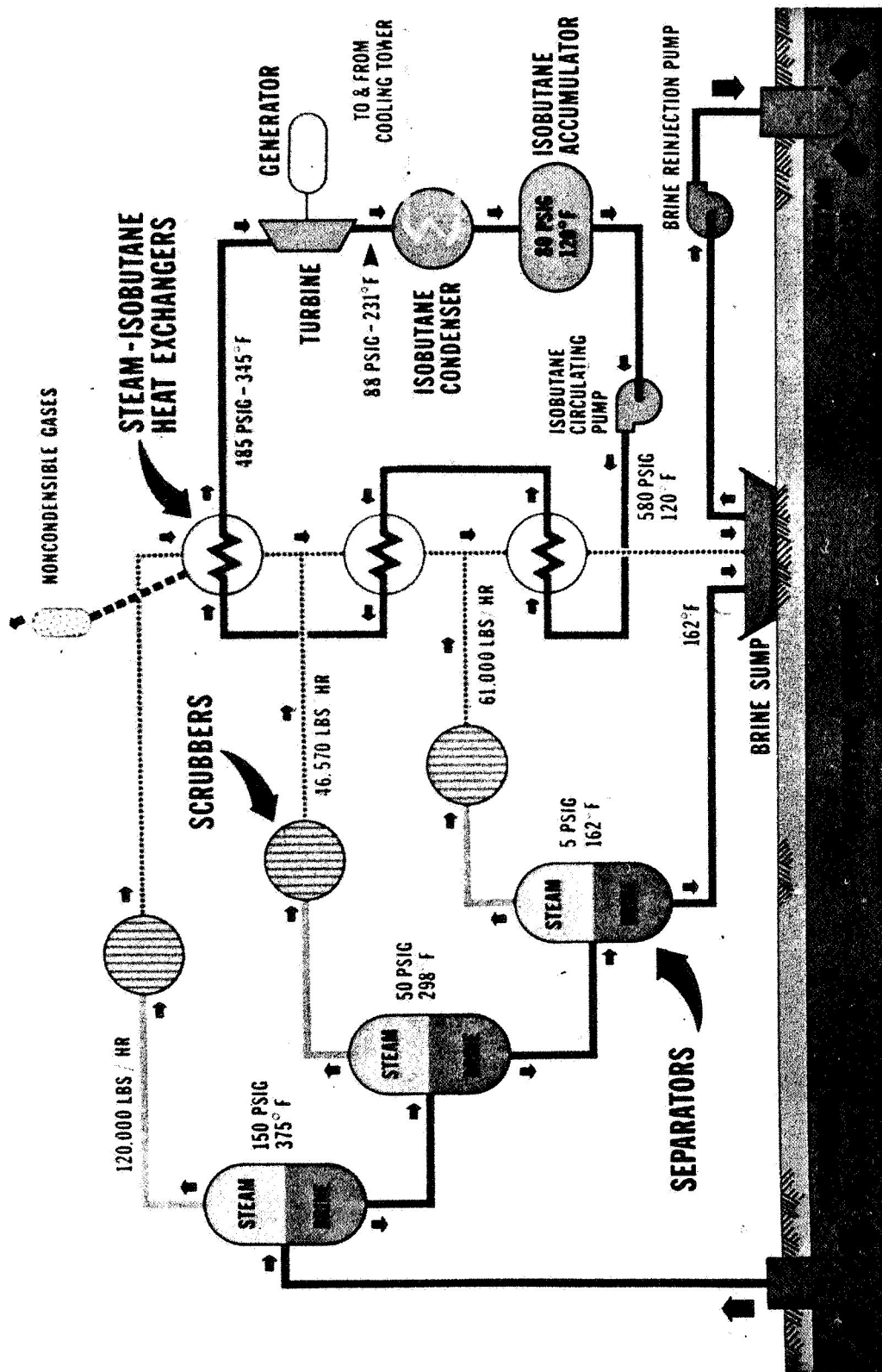


Fig. 8. Three-stage steam flash

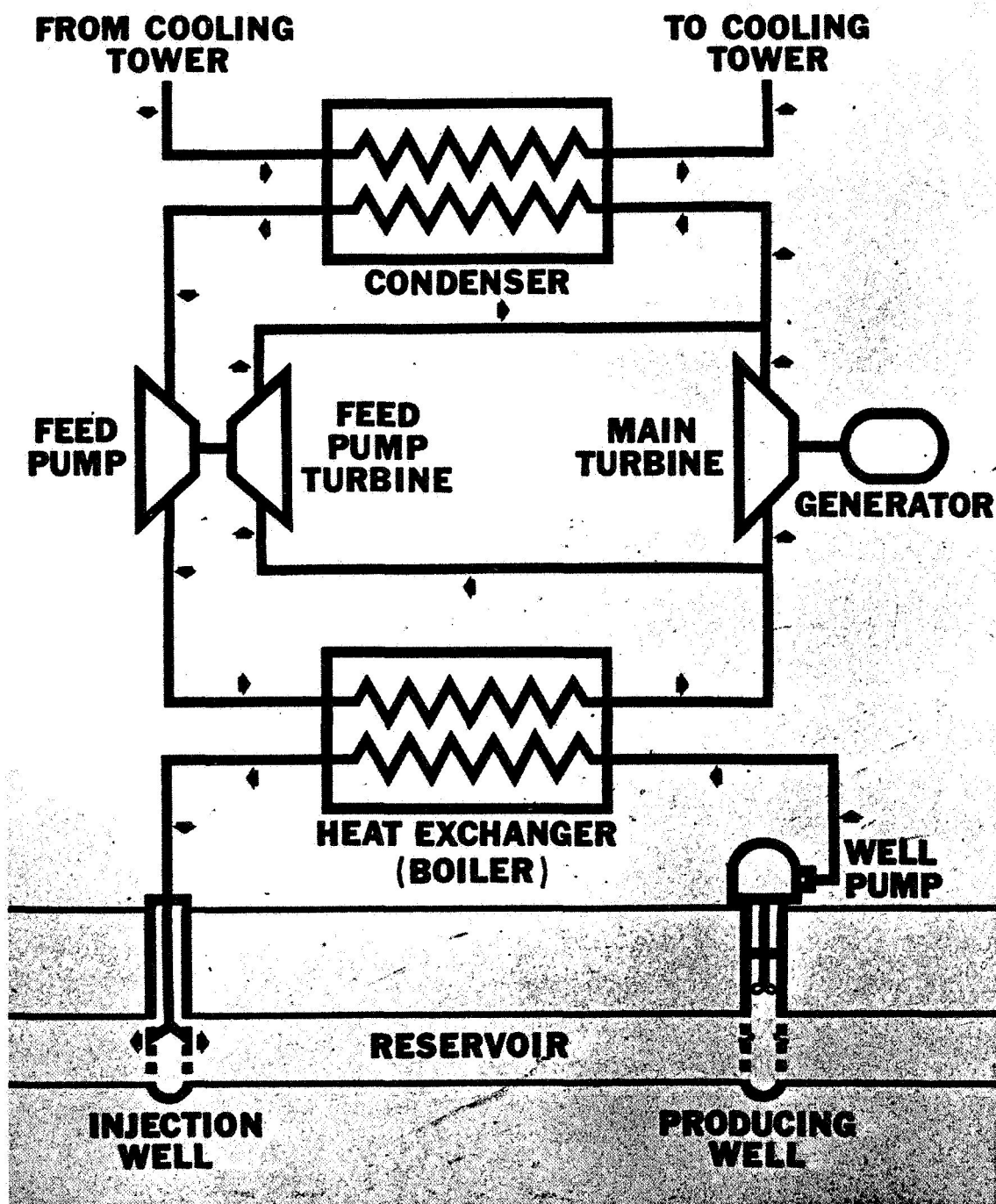


Fig. 9. Magmamax process

PROGRESS OF THE LASL DRY HOT ROCK GEOTHERMAL
ENERGY PROJECT*

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Under sponsorship of the Division of Applied Technology of AEC, Los Alamos Scientific Laboratory is investigating the possibilities and problems of extracting energy from geothermal reservoirs which do not spontaneously yield useful amounts of steam or hot water. The system for accomplishing this which is being developed first is a pressurized-water circulation loop intended for use in relatively impermeable hot rock. It will consist of two holes connected through the hot rock by a very large hydraulic fracture and connected at the surface through the primary heat exchanger of an energy utilization system. Preliminary experiments in a hole 2576 ft (0.7852 km) deep, extending about 470 ft (143 m) into the Precambrian basement rock underlying the Jemez Plateau of north-central New Mexico, revealed no unexpected difficulties in drilling or hydraulically fracturing such rock at a temperature of approximately 100°C, and demonstrated a permeability low enough so that it appeared probable that pressurized water could be contained by the basement rock. Similar experiments are in progress in a second hole, now 6701 ft (2.043 km) deep, about 1.5 miles (2.4 km) south of the first one. Here the bottom-hole temperature is about 146°C, and again no unexpected difficulty was encountered in drilling or hydraulically fracturing the granitic basement rock. At least below about 4250 ft (1.295 km) the permeability of the basement rock is also very low at this location, and again the rock appears competent to contain a pressurized-water circulation system.

I. INTRODUCTION

Many areas are known in the United States and elsewhere in the world in which geothermal gradients are relatively high but the formations accessible by drilling from the earth's surface do not yield commercially useful amounts of natural steam or hot water. In the same sense that an oil or gas well is considered a "dry hole" if it does not produce enough oil or gas to pay out the cost

*This work is being done under the auspices of the U. S. Atomic Energy Commission.

of drilling, a geothermal well drilled into such a formation is considered a dry hole if it does not produce enough steam or superheated water to pay for the well. Similarly, the natural thermal reservoir into which such a well has been drilled can be described as a "dry geothermal reservoir" even if (as is usually the case) it is not completely devoid of moisture.

There are several reasons why, in this sense, a geothermal reservoir may be "dry." One is that, because of faulting or an overlying impermeable formation or simply an extremely arid climate, very little water ever reaches the hot rock. In this case a dry geothermal reservoir might, locally, be converted into a productive wet one by developing a water-flooding system: drilling one or an array of holes through which cool water would be injected and a second array through which heated water or steam could be recovered. A second possible reason for a geothermal reservoir to be dry is that the permeability of the rock composing it is too low to permit whatever fluid it contains to flow into a well at a usefully high rate. Here a stimulation technique such as acidizing or fracturing the rock either hydraulically or by use of explosive might make the reservoir economically productive. A third possibility is that the reservoir is deficient in both moisture and permeability, and it is with this possibility that the LASL "Dry Hot Rock" Geothermal Energy Project is initially concerned. It is hoped that the other possibilities listed, and several variations of them with the geologic environment, can also eventually be investigated in a continuing, long-range program directed toward making this vast energy supply economically useful.

II. MAN-MADE CIRCULATION LOOPS

A variety of methods have been suggested for extracting energy from dry hot rock in the earth's crust. The simplest of these, and probably the most economical, appears to be to imitate nature by using water as a heat-transport fluid—injecting it into the geothermal reservoir at one point; permitting it to circulate over a sufficient surface area to be heated essentially to the temperature of the rock; and then recovering it at a second point as either hot water or steam. Again, a number of variations of this general method are possible, and eventually several of them should probably be tried in the field. The most straightforward of these appears to be to drill two separated holes from the surface downward into the hot rock and then to permit water to circulate through the formation continuously from one hole to the other. However, if the initial permeability of the rock is high enough to permit this circulation to occur naturally, then the rate of water loss from the system into the surrounding formations can also be expected to be high. To conserve both water and heat, it would be preferable to create the circulation loop in rock whose inherent permeability is low enough so that it will effectively contain the circulating heat-transport fluid. This permeability requirement is probably met by many deeply buried shales, limestones, dolomites, and both igneous and metamorphic rocks—although that remains to be demonstrated by in situ experiments.

When hot rock of low permeability has been found, the principal problems that remain are those of drilling the necessary holes and creating between them a connection whose impedance is low enough to permit a high rate of fluid circulation, and whose surface area is large enough to permit a high rate of

heat extraction to be maintained for a usefully long time. At least to depths of the order of 20,000 ft (6 km) and rock temperatures of the order of 300°C, the necessary drilling can evidently be done with existing equipment and techniques. Several methods then exist for creating a connection between the holes, including chemical leaching to increase the permeability of the rock locally; fragmentation by detonation of either chemical or nuclear explosives; and hydraulic fracturing. Of these, hydraulic fracturing is the method that will be tried first in the LASL project.

III. HYDRAULIC FRACTURING

Hydraulic fracturing is a method of well completion that has been used extensively for about 35 years in oil- and gas-bearing formations of relatively low permeability, to increase the rate at which petroleum or natural gas flows into a well. It is done hundreds of times a week by commercial oil-field service companies, with no evident hazards or undesirable environmental effects. It is accomplished by using "packers" (temporary seals) in a well to isolate the zone in which it is desired to produce a fracture, and then using a high-pressure pump at the surface to pressurize this zone sufficiently to crack the rock around the wellbore. The pumping pressure required to fracture the rock is normally from a few hundred to a few thousand pounds per square inch (of the order of 2 to 20 MPa), and once a crack has been formed it is in general easier to extend that crack than to form a new one. The result of hydraulic fracturing is, then, believed normally to be a single "penny-shaped" crack, extending outward from the well to distances of the order usually of a few hundred feet (100 to 200 m) but occasionally — as a result simply of continuing to pump fluid into the crack — to distances as great as half a mile (0.8 km) or more. If the fracture is formed near the earth's surface, then the fluid pressure required to create it is also usually sufficient to lift the overburden above it, and the plane of the fracture is therefore expected to be horizontal. However, at depths greater than about 2000 to 3000 ft (0.6 to 0.9 km), the least compressive stress in the rock — against which the crack will naturally open — is in general horizontal, so that the plane of a deep penny-shaped crack is expected to be vertical.

Not much is known from direct observation about the detailed geometry of a large hydraulic fracture. However, with the usual assumptions that a deep hydraulic fracture is vertically oriented, circular in outline, and elliptical in cross-section, and with realistic values of the properties and geothermal gradient of the rock containing the fracture, it is possible to construct what are believed to be good computer models of heat flow and fluid flow in such a crack. In rock of relatively low permeability it should be possible to hold the crack open simply with fluid pressure, without the use of particulate proppants. If this can in fact be done, our computer analyses indicate that impedances will be low enough to permit buoyant circulation of water in the crack; that very little short-circuiting will occur between the injection and the recovery hole; and that efficient extraction of heat from the crack surfaces will be possible. Under these conditions, and in spite of the expense of drilling deep holes in hard rock, the cost per unit of heat extracted from dry hot rock should be low relative to that of heat from almost any other energy source.

IV. THE LASL PROJECT

Under sponsorship of the Division of Applied Technology of the U.S. Atomic Energy Commission, Los Alamos Scientific Laboratory has undertaken to investigate the possibilities, problems, and economics of creating and operating such an energy extraction system. Initial field investigations are in progress on the Jemez Plateau of north-central New Mexico, about 20 air miles (32 km) west of the city of Los Alamos. The particular area being studied now is just outside of the western rim of the Valles Caldera, within which volcanic activity has occurred as recently as 40,000 to 50,000 years ago. This is recent enough in geologic time so that hot rock still exists at moderate depths, and contributes substantially to terrestrial heat flow in the area.

Because of its accessibility and inherent geologic interest, the region of the Valles Caldera has been studied intensively for many years by the U.S. Geological Survey, the New Mexico Bureau of Mines and Mineral Industries, several universities, and a number of other organizations and individuals. On the basis of information from these sources, supplemented by that from our own geologic and heat-flow studies, LASL has concentrated its attention on an area close to but outside of the caldera rim, where heat flow is relatively high, depth to the crystalline basement rock is moderate, geology is uncomplicated, and no large or active faults have been found.

In our first deep exploration of this area, a hole ("GT-1") was drilled in 1972 to a total depth of 2576 ft (0.7852 km), penetrating about 470 ft (143 m) into the Precambrian basement. Rock temperature at the bottom of this hole was about 100.4°C. The Precambrian section investigated consisted of granitic rocks typical of the southern Rocky Mountains, which showed extensive high-angle fracturing. However, the fractures were in general well sealed with calcite or chlorite, and measured in situ permeabilities were very low. Using our own equipment and relatively low pumping rates, we produced a series of small hydraulic fractures at pumping pressures of about 1200 to 1700 psi (8.3 to 11.7 MPa). Breakdown pressures correlated well with the apparent competency of the rock as observed on core samples. Using much larger equipment and higher pumping rates, an oil-field service company subsequently produced two larger fractures in the basement rock at pumping pressures of about 2500 psi (17.2 MPa). In a long series of pressurization and depressurization experiments, we measured an apparent surface energy of the in situ rock of about 100 J/m², a least horizontal compressive stress in the lower part of the hole of about 2000 psi (13.8 MPa), and a permeability of newly exposed fracture surfaces of a small fraction of a millidarcy. The fractures produced appeared to be essentially vertical, with a northwest-southeast orientation. These results were encouraging with regard to the existence under the Jemez Plateau of a dry geothermal reservoir, the possibility of drilling into and hydraulically fracturing it to produce a man-made geothermal energy system, and the probability that a pressurized-water circulation loop could be contained by it without excessive loss of the heat-transport fluid.

To confirm these observations at another location and to permit similar measurements to be made at greater depths and under conditions of higher temperature and pressure, a second exploratory hole ("GT-2") has been drilled

during 1974 at a location about 1.5 miles (2.4 km) south of the first one. Its present depth is 6701 ft (2.043 km), although we hope to deepen it further, and we are now engaged in a series of hydrologic, hydraulic-fracturing, and pressurization and depressurization experiments in it. Some geologic surprises were encountered in the volcanic and sedimentary section above the crystalline basement rock, and the lithology of the Precambrian basement section is considerably different from that observed in GT-1. However, the fracture pattern in the basement rock is quite similar to that seen in cores from the previous exploratory hole. In GT-2 a highly permeable region of unsealed fractures was encountered in the granitic section at a depth of about 3570 ft (1.088 km), with some evidence of additional unsealed fractures at two or three other horizons in a zone several hundred feet deep which contained this region. Both above and below that zone the natural fractures in the basement rock are well sealed with such minerals as calcite and quartz, and measured in situ permeabilities again are very low (of the order of 20 microdarcies or less). There is some evidence that the natural fractures are both less frequent and more tightly closed at greater depth in the section.

At the location of GT-2, heat flow is evidently a little less than at GT-1. Since the effects of cooling by the drilling fluid have largely disappeared, the geothermal gradient through the Precambrian section of GT-2 from about 2400 to about 6700 ft (0.73 to 2.04 km) has become nearly constant at approximately 50°C/km. Rock temperature at 6701 ft (2.043 km) is about 146°C, and we are now projecting with reasonable confidence to a temperature of at least 200°C at a depth of 10,000 ft (3.05 km).

In our first hydraulic fracturing experiments, at a depth of about 6600 ft (2.01 km) and a pumping rate of 120 gpm (454 l/min), fracture has occurred at a pumping pressure of about 2500 psi (17 MPa). As was true of several of the experiments in GT-1, fracturing has apparently occurred by slow opening and extension of favorably located preexisting cracks rather than by the sharp breakdown of competent rock. As fracturing theory predicts, crack extension then occurs at slowly decreasing pressure. The largest fracture so far produced was made by injecting about 900 gal (3400 l) of water. It is being further extended today. So far no attempt has been made to prop the fractures produced in GT-2, and fluid return has generally been very slow when pressure in the hole was reduced and the crack was permitted to collapse. However, about 70 to 75% of the water injected has usually been recovered within a few hours, and the rest can be accounted for either by permeation of newly exposed crack surfaces or by entrapment of fluid in a crack which has sprung shut in the region of stress concentration near the borehole, or by some combination of the two. The system represented by the hole and the fractures extending from it appears to be a very tight one.

Experiments in GT-2 will continue for some time at the present depth, after which it is hoped that the hole can be extended and generally similar experiments can be undertaken in the deepened hole.

V. CONCLUSIONS

While two exploratory holes represent a very small sample, it so far appears that the Precambrian basement rock underlying the Jemez Plateau of northern New Mexico satisfies our definition of a "dry geothermal reservoir." No unexpected difficulties have been encountered in drilling or hydraulically fracturing this rock, and except for one zone about 1000 ft (0.3 km) below the Precambrian surface, its permeability is extremely low. In general it appears competent to contain pressurized water, and no reason has so far been discovered to believe that a man-made, pressurized-water circulation loop cannot be created and operated within it substantially as has been described above. Therefore we are still very optimistic that the LASL Geothermal Energy Project will be successful in developing economical methods for extracting thermal energy from dry hot rock in the earth's crust.

THE MARYSVILLE, MONTANA GEOTHERMAL PROJECT

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Drilling the first geothermal well in Montana presented many challenges, not only in securing materials and planning strategies for drilling the wildcat well but also in addressing the environmental, legal, and institutional issues raised by the request for permission to explore a resource which lacked legal definition. The Marysville Geothermal Project was to investigate a dry hot rock heat anomaly. The well was drilled to a total depth of 6790 feet and many fractured water bearing zones were encountered below 1800 feet.

I. INTRODUCTION

The object of the Marysville Geothermal Project is to investigate a region of abnormally high geothermal heat flow near Marysville, Montana, about 20 miles northwest of Helena. The research should determine the nature and size of the resource, how the energy might be extracted, the potential monetary value of the energy, and how similar resources elsewhere might be located. The heat source was expected to be a granitic pluton or magmatic intrusion, 10,000 to 40,000 years old, with temperatures in the range of 300 to 500°C. Originally it was thought that the pluton was at relatively shallow depths, but at present its depth and exact location are unknown.

During the period from 1966 until the beginning of this project in 1973, Dr. David Blackwell, Associate Professor of Geophysics at Southern Methodist University (SMU), made extensive heat flow measurements in the vicinity of Marysville under the sponsorship of the National Science Foundation (NSF) and the U.S. Geological Survey. Heat flow data were obtained from 15 relatively shallow drill holes (less than 1000 ft) which existed in the area as a result of previous mineral explorations. The heat flow from the 15 sites ranged from 3.1 to 19.5 heat flow units (hfu) in $\mu\text{cal}/\text{cm}^2/\text{sec}$. (For comparison, the western Montana average is 1.9 hfu and the worldwide average is believed to be 1.5 hfu.) The maximum heat flow corresponds to a geothermal gradient of 240°C/km. In spite of these extremely high gradients there are no surface manifestations in the form of hot springs or geothermal activities within approximately 20 miles of the site. Consequently, this region is known as a blind geothermal anomaly.

In February 1973 Battelle-Northwest (BNW) submitted a proposal to investigate this anomaly to the NSF for a three-year research project at a cost of approximately \$2,100,000. The project was funded in June 1973 by NSF, which allocated \$265,000 for CY-73 and authorized \$1,780,000 for CY-74.

During the summer of 1973, SMU conducted surveys of the geology, heat flow, gravity, magnetic field, and microseismic noise in the Marysville area. In addition, infrared aerial surveys were conducted by Battelle-Northwest. Heat flow measurements were made in nine additional shallow holes drilled under Dr. Blackwell's direction to obtain a better definition of the size of the heat flow anomaly. By October 1973 the results of these various field surveys enabled the team to pick a site for drilling a deep well. The site selected was approximately 1/4 mile downstream from the Empire Mine and about four miles west of Marysville on land administered by the Bureau of Land Management (BLM). On October 26, 1973 the NSF conducted a review meeting of the project in Helena, which was attended by members of the State and Federal Governments as designated by the NSF. A preliminary report provided to the reviewers at that meeting has now been superseded by a first annual report published in the spring of 1974. As a result of the review meeting, NSF authorized the next phase of the work which was undertaken in CY-74.

Once a decision was made to undertake the new work, Battelle-Northwest and Rogers Engineering Company prepared a draft environmental analysis for the BLM. Additional environmental analyses were conducted by BLM to cover 1974 work only (primarily the drilling of the deep well). BLM determined that no environmental impact statement would be required for CY-74 activities but that a new review would be required for activities beyond that time.

Following the site selection, Rogers Engineering Company prepared site engineering surveys and plot plans for the drilling operations. The necessary Use Permits were obtained from the Bureau of Land Management, the U.S. Forest Service, the Montana State Division of Water Use, and the Montana State Lands Department. Following these activities Rogers Engineering Company prepared specifications for the site construction and drilling of the deep well. For the site construction, the low bid was received from and the contract awarded to the William Miller Construction Company, Missoula, Montana, in April 1974. Similarly, the drilling contract was awarded to the Molen Drilling Company of Billings, Montana, in May 1974.

II. SUMMARY OF DEEP WELL DRILLING OPERATION

The drilling operation was scheduled to begin about June 1, 1974, after surface preparations were completed at the site. Ninety days of drilling were planned to achieve a target depth of 6000 ft. The actual drilling began on June 10 and continued until August 30, a period of 81 days ending at a total depth of 6790 ft, as shown in Fig. 1. Most of the drilling was done with aerated water at rates of 18 to 25 ft/hr. Two major formations were encountered. The upper formation of Empire Shale (metamorphosed shale and quartzite) extended to approximately 975 ft, and the remainder of the hole to depth was in the Empire Stock (quartz feldspar porphyry). There is a gradual change in the Empire Stock with depth toward a granite, showing the effects of slow cooling.

The well profile and casing schedule are shown in Fig. 2 along with the 12 major fracture zones.

The Empire Stock is extensively fractured and contains a large volume of water. Water was first encountered at 1525 ft, and major water zones were found at 1912 and 3386 ft. However, the many fractures led to speculation that the water zones are interconnected. All of the fracture zones below 1000 ft appear to contain water, and in some cases we encountered flows in excess of 250 gallons/minute from upper fracture zones into the lower ones. It is not clear to what extent water was injected in lower formations during drilling. In view of all of the geophysical surveys that had been done at the surface, including electrical resistivity and magnetotellurics, large amounts of water had not been expected.

Schlumberger Well Services were contracted to log the hole before the middle-string casing was set to 1326 ft. Later they logged the remainder of the hole. Their logs include:

- (1) Bore hole caliper (bhc), sonic, and gamma ray log, which measures the hole diameter, the acoustic velocity, and the natural radioactivity of the rock.
- (2) Dual induction laterolog, which determines formation resistivity by eddy current induction and flow of a focused direct current.
- (3) Formation density, gamma ray, and caliper log, which determines the formation density, hole diameter, and natural radioactivity.
- (4) Compensated neutron log, which measures the formation porosity and hydrogen concentration by means of a neutron source.
- (5) Electrical survey, which measures resistivity of the formation.
- (6) A 4-arm digital dipmeter, which measures the dip angle and dip direction of fractures and bedding planes by correlating changes of formation electrical resistivity.
- (7) Temperature logs with a platinum resistance thermometer.
- (8) Water flow logs: open hole spinner, packer flowmeter, and radioisotope.

Results of these logs are now being analyzed.

Cutting of cores was undertaken 18 times during the drilling operations and produced 15 useful cores and 1 set of fragments. The depths at which the 15 cores were taken are shown in Fig. 2 on the left-hand side of the well profile. Despite the use of diamond coring bits, it was still difficult to obtain good cores. Costs for the coring operation were quite high, and we are now estimating approximately \$11,000 per linear foot of recovered core. The cores have been cataloged and are now being cut, and scientific analysis is expected to begin soon.

The wellhead equipment, as shown in Fig. 3, is mounted on the 13-3/8-in. casing, which is cemented firmly to the formation to a depth of 1326 ft; in addition the 20-in. surface casing is cemented to a depth of 115 ft. The two gate valves on the wellhead can be opened to allow further scientific activities and measurements to proceed in the hole throughout the winter. In the event of a rapid hole heat-up and an increase in pressures, the 9-5/8 in. casing is free to expand upward into the spool; and the competent cementing jobs on the upper casings are entirely adequate to withstand high pressures. The 9-5/8 in. casing can be removed if the well should later be abandoned or it can be cemented in place if conditions so dictate.

III. WELL TEMPERATURES AND FLOW RATES

Rock temperature measurements were made with difficulty because of water flow in the hole throughout the entire drilling operation. In every case measured to date, the flow has been down the hole with the lower formations taking water from the upper ones. Flows in excess of 250 gallons/minute were encountered prior to setting the casing as shown in Fig. 4. The source of this large flow seemed to be the fracture zone between 3386 and 3410 ft. However, flows less than 50 gallons/minute were believed to originate from the upper parts of the hole, probably from the 1912- to 1936-ft zone. The open hole spinner test was not particularly sensitive to low flows in the large diameter hole, so accurate data above the 3400-ft level was difficult to obtain as indicated by the dotted line in Fig. 4. Data obtained near the bottom of the hole (not shown in Fig. 4) indicate that most of the 250-gallon/minute flow was going back into formation at the bottom of the hole in the fracture zone below 6723 ft. The hydrostatic pressure of this zone was apparently less than that of the upper zones, allowing the downflow of water. Whether the water flow was a local transient condition that would have stopped within a few days or a condition that might exist for a long period of time is unknown. However, the drill stem test did not show any large hydrostatic head difference between the lower and upper zones.

After the casing was set and the cement plug established in the bottom of the hole, flows were significantly reduced as shown in the lower part of Fig. 4. Approximately one gallon/minute is leaking through the perforations in the casing made for the second cement job and flows immediately beneath the casing increased to approximately 10 gallons/minute. Between September 10, when the packer flowmeter test was performed, and September 22, when the radioisotope test was done, an apparent equilibrium took place in a lower part of the hole since the flow at the 5700-ft level reduced from greater than 30 gallons/minute to approximately one gallon/minute. Below the 6000-ft level the flow is zero to the best of our ability to measure it with the isotope test. The last flow test, made on November 17, 1974 (not shown in Fig. 4) with the radioisotope instruments, shows a maximum flow of about one gallon/minute at about 4270 ft. Additional flow tests are planned to determine if further changes are taking place in the hole.

Downhole temperature measurements were made four ways: (a) using Dr. Blackwell's resistance element thermometer, which is limited to maximum

depths of approximately 2500 ft and maximum temperatures of approximately 110°C; (b) using the Schlumberger platinum resistance thermometer; (c) a Kuster downhole temperature vs. time recorder; and (d) maximum reading mercury thermometers. Generally the data obtained by Blackwell in the upper part of the hole tends to complement the Schlumberger measurements shown in Fig. 5 and indicates cooling of the formation as drilling proceeded. The apparent erratic behavior of fine details is presumably caused by the in-flow of water from formations before and after the setting of the casing. The logging on September 10 (curve 2) occurred within a few hours after most of the cool water in the mud pit had been pumped back into the hole, and, consequently, cooler temperatures were recorded at that time. Also, two additional Schlumberger logs were made approximately 24 hours after the August 31 log (curve 1), and these agree quite closely with those of curve 3, which were obtained on September 21. Temperatures of curve 1 were obtained before the casing was in place and those of curves 2 and 3 afterwards. Water moving down the annulus between the 9-5/8-in. casing and the hole is affecting the temperature readings in the casing. Below the casing the water flows of approximately 10 gallons/minute are sufficiently high to prevent measurement of the ambient rock temperature, and generally this condition exists down to the 5700-ft level. Water temperatures slightly less than 200°F were obtained throughout this entire region. Maximum temperature thermometer readings over the same region read consistently 200 to 204°F and are probably the most reliable of the measurements. The Kuster instrument was left on the bottom of the hole for 44 hours between September 19 and 21, but it showed no temperature increase above 204°F. Since the flow rates in this region are believed to be zero or very low, it appears that the rock temperatures may not be greatly in excess of 200°F in the immediate vicinity of the hole. However, an additional period of perhaps one month will be required to allow the downhole temperatures to stabilize before valid conclusions can be drawn. Additional temperature measurements will be made throughout the winter months and flow in the bottom of the hole can probably be reduced to zero (if it is not at this time) by the use of wire line packers.

Numerous water samples have been taken throughout the drilling operation at various depths and are now undergoing chemical analyses at the SMU and BNW Laboratories. Although the water samples have been contaminated with soap and lubricants from the drilling operations, they show only 24 parts/million chloride content and, consequently, the water is not saline. Water samples from the upper part of the hole contained less than 1,500 parts/million total dissolved solids in spite of contamination from the drilling operations. Geothermometer data from silica concentrations indicate a temperature of approximately 250°F, which seems to be consistent in nearly all of the water samples. The potassium, sodium, calcium ratios indicate a temperature of approximately 350°F. The effects of dilution of the underground water by surface water have not been determined. Work on the water samples is continuing and will tie in closely with the chemical analyses of the cores.

In conclusion, downhole temperature measurements made to date indicate temperatures of approximately 200°F, but the hole has not yet reached thermal equilibrium. Studies are planned throughout the winter months.

IV. GEOPHYSICAL SURVEYS, 1974

Geophysical surveys undertaken during the summer of 1974 included geologic mapping of heat flow to the south of the presently explored area and additional gravity, magnetic, and microseismic studies.* Work on these studies began in early May and by mid-June a crew of six scientists and graduate students were working at the field. Four additional shallow holes were drilled to the south in which additional heat flow measurements are being made. Data from all of these geophysical surveys are undergoing analysis at SMU, and conclusions are not yet available. Work on these data will continue throughout the winter months.

V. WINTER 1974-1975 STUDIES

As previously indicated, logging of the well for temperature and flow studies will continue for some time as weather permits. Other studies, which are just now beginning, include: analyses of the cores, geochemistry studies, thermal equilibrium studies, and further analysis of the geophysical data from the surface surveys. Additional studies being considered at this time include regional hydrology, analysis of satellite data, and geophysical model development. If more drilling is contemplated in the region, an additional environmental analysis will be required.

Because many of the results obtained to date were not anticipated, despite extensive geophysical surveys, much information of scientific value is being generated. This information will undoubtedly be useful in the future to help reduce the risk factors in developing new geothermal energy resources.

VI. SPONSOR AND CONTRACTOR IDENTIFICATION

The sponsor of this research is the RANN Division of the National Science Foundation, and the project is under the direction of Dave Lombard. The project total cost is approximately \$2,100,000 extending over a three-year period. The prime contractor for this work is Battelle-Northwest at Richland, Washington, under the direction of Donald H. Stewart, Manager of Geothermal Programs, and William R. McSpadden, Project Manager. Rogers Engineering Company of San Francisco, California, is the architectural engineering firm and is responsible for the deep well drilling operations and site construction work. Their work was under the direction of James T. Kuwada, Vice President, and W. F. Bott, Project Engineer. The geophysical surveys were performed by a team of scientists and graduate students from Southern Methodist University in Dallas, Texas, under the direction of David D. Blackwell, Associate Professor, Department of Geological Sciences. Thermal analysis and modeling have been done by Systems, Science and Software of La Jolla, California, under the direction of Russell E. Duff, Manager, Radiation and Fluid Physics Division.

*For a more complete description of these surveys see the following paper in Session II: D. D. Blackwell, Assessment of the Geothermal Anomaly Near Marysville, Montana.

Additional information on the project can be obtained by writing to William R. McSpadden, Mathematics Building, Battelle-Northwest, Richland, Washington 99352.

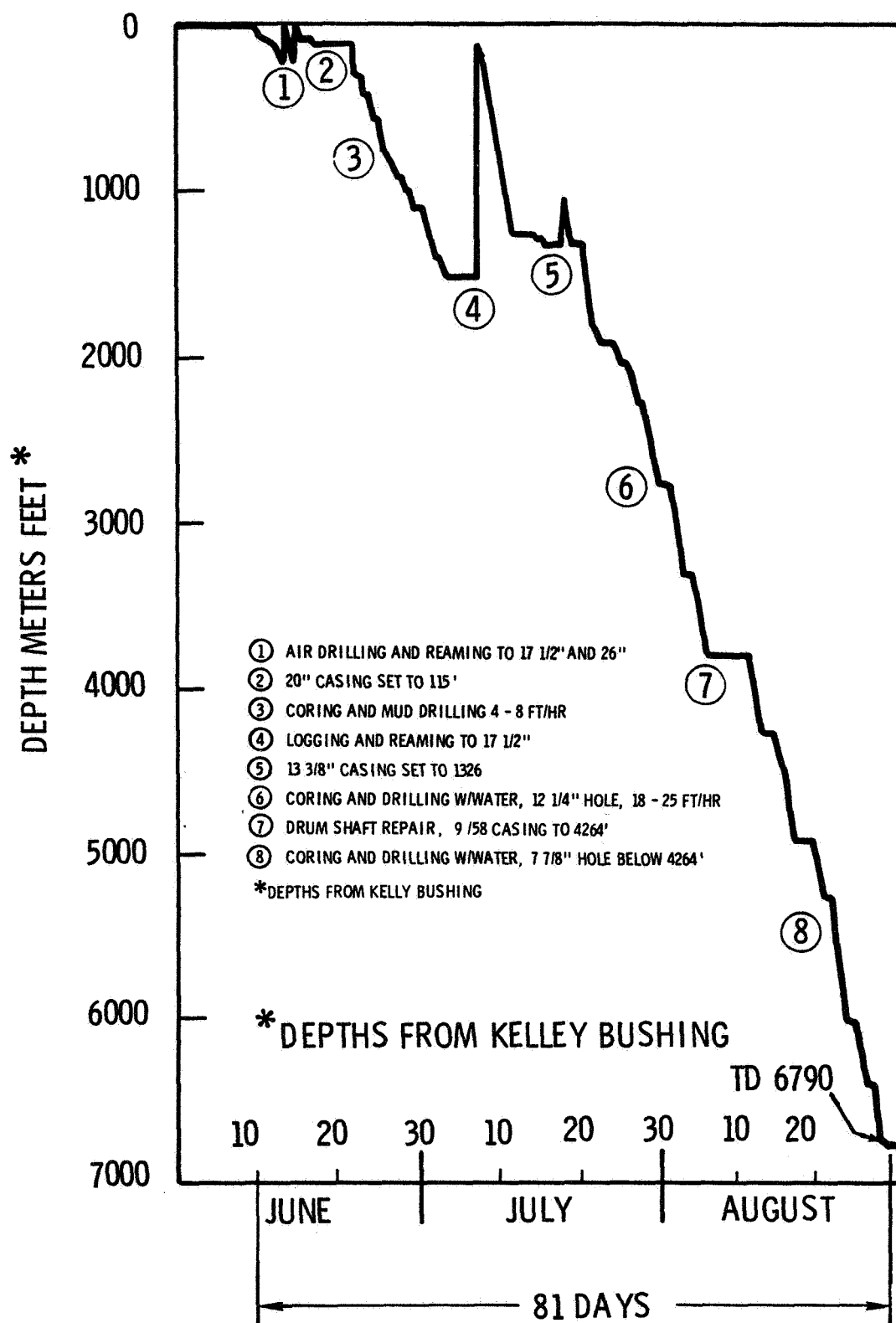


Fig. 1. Marysville Geothermal Project drilling record, well No. 1

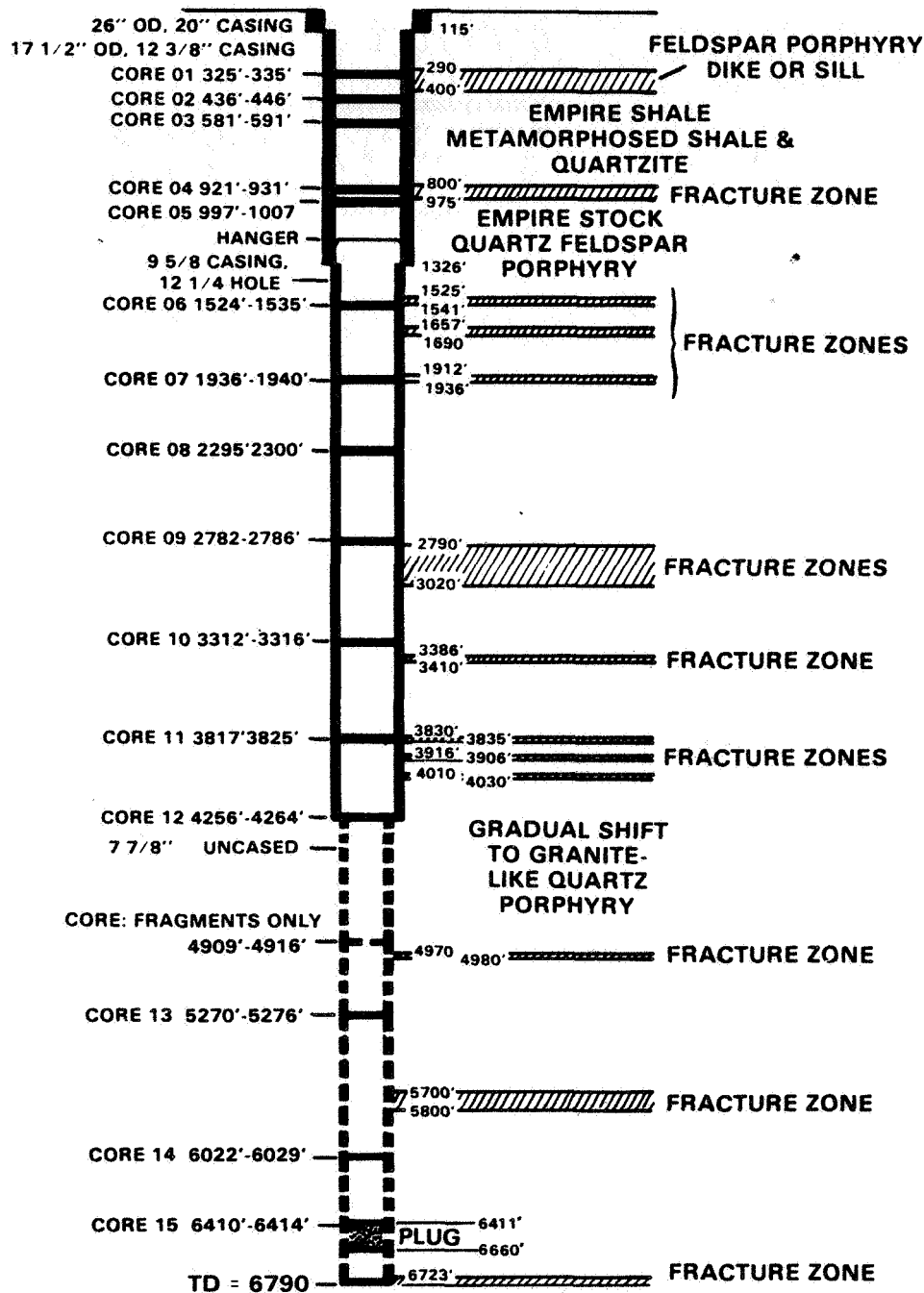


Fig. 2. Casing, coring, and formation data, well No. 1

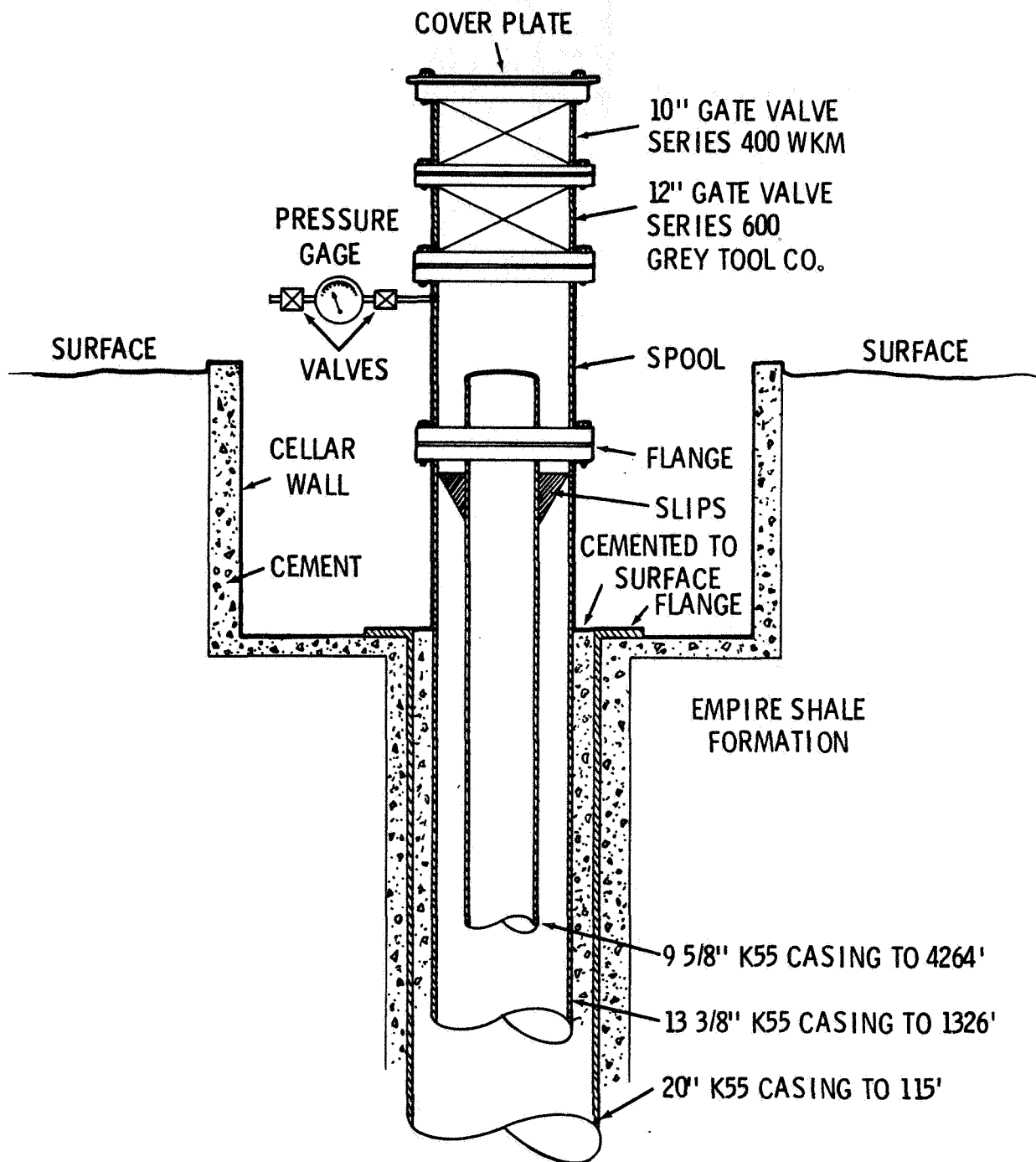


Fig. 3. Wellhead equipment, September 1974

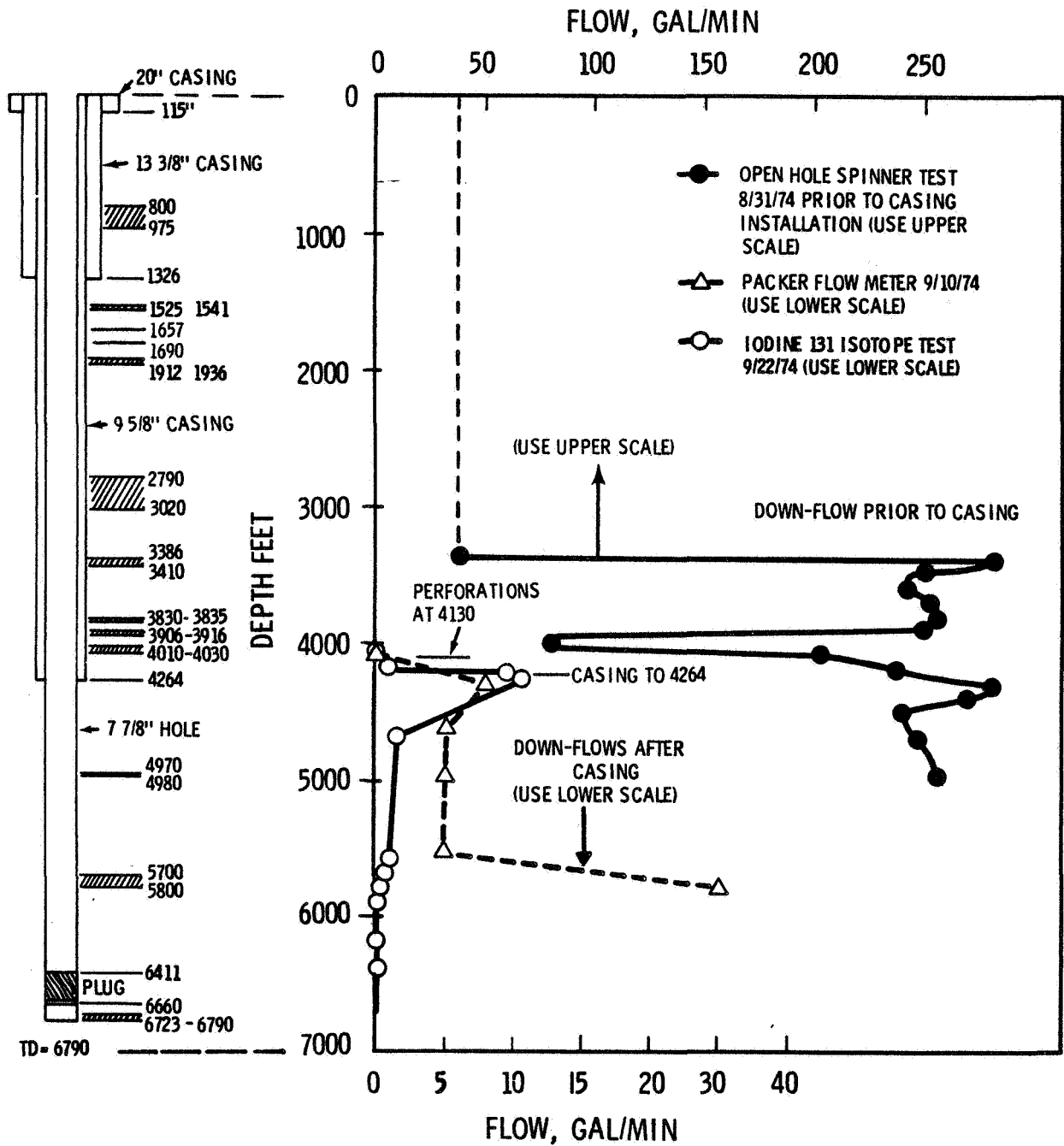


Fig. 4. Flow rates, well No. 1

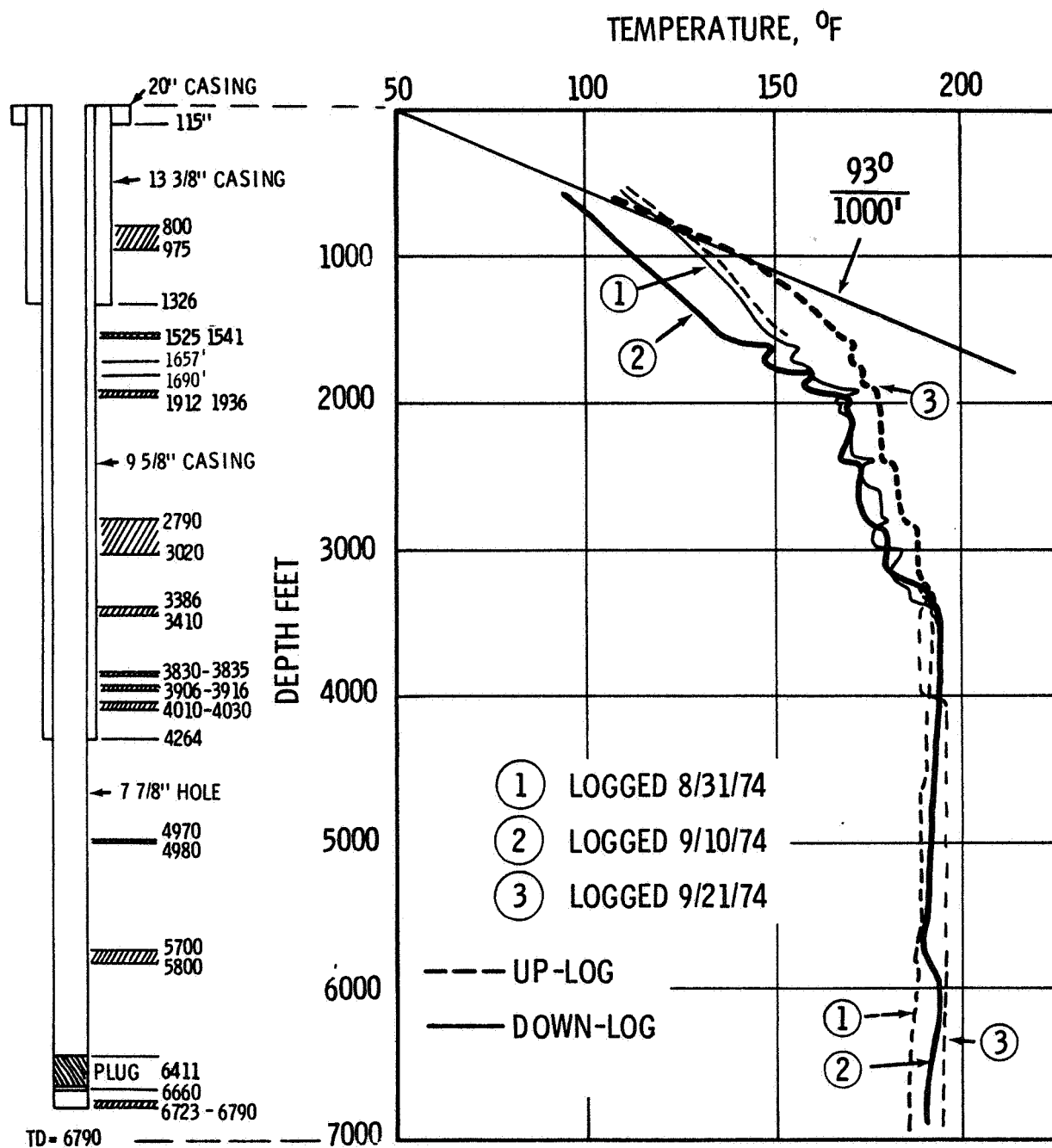


Fig. 5. Well temperatures, well No. 1

PRELIMINARY RESULTS OF GEOTHERMAL DESALTING
OPERATIONS AT THE EAST MESA TEST SITE
IMPERIAL VALLEY, CALIFORNIA

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The Bureau of Reclamation has erected at its Geothermal Resource Development site two experimental test vehicles for the purpose of desalting hot fluids of geothermal origin. Both plants have as a feed source geothermal well Mesa 6-1 drilled to a total depth of 8,030 feet and having a bottom hole temperature of 400°F. Formation fluid collected at the surface contained 24,800 mg/l total dissolved solids. The dissolved solids consist mainly of sodium chloride.

A multistage distillation (3-stage) plant has been operated intermittently for one year with no operational problems. Functioning at steady-state conditions with a liquid feed rate of 70 g/m and a temperature of 221°F, the final brine blowdown temperature was 169°F. Product water was produced at a rate of about 2 g/m; average total dissolved solids content of the product was 170 mg/l. A product quality of 27.5 mg/l at a pH of 9.5 was produced from the first stage.

The second distillation test vehicle, a vertical tube evaporator, consists of two units: a single-effect unit and a three-effect unit. All components are constructed of carbon steel. The single-effect unit was operated a total of 50 hours for intermittent shakedown tests. After inspection and chemical cleaning, the unit was operated continuously for 100 hours. During the last 24 hours of steady-state running, the unit was operated with a 302°F steam feed at a ΔT of 16°F, producing a concentration factor of 1.07. A heat transfer coefficient has been calculated as 405 Btu/hr-sq ft-°F; this value remained constant during the last 24 hours. The product (steam feed condensed at a rate of 0.8 g/m) had a total dissolved solids content of less than 10 mg/l. Inspection indicated minor corrosion products with no visible evidence of carbonate or silica scale. The three-effect unit is currently undergoing shakedown operations.

I. INTRODUCTION

The Bureau of Reclamation is currently exploring the geothermal resources of Imperial Valley, California. The primary objectives of the program are to demonstrate the feasibility of desalting geothermal fluids for development of needed high-quality water supplies in the southwest and to investigate the production of electric energy concurrently with desalted water. These aspects are reported in more detail elsewhere in this proceedings (Ref. 1). As a part of this geothermal resource development program, two types of test desalting units have been installed at the Bureau of Reclamation East Mesa test site.

Current research at the East Mesa test plants has not only direct application to desalting of geothermal fluids, but also direct application to heat exchanger design for power development using geothermal fluids.

The Imperial Valley test production wells, desalting plants, and a brief review of desalting data will be described.

II. THE IMPERIAL VALLEY

The Imperial Valley is an extensive sedimentary basin characterized by high heat flow. The valley is part of a structural depression known as the Salton trough that extends northwest from the Gulf of California. Late tertiary sediments filling the depression consist predominantly of unconsolidated sand, silt, and clay with some gravel. As these sediments are saturated to within a few tens of feet of the land surface, the Imperial Valley constitutes a large potential geothermal reservoir. Rex described geophysical work done in the Imperial Valley (Ref. 2), and a summary of more recent geophysical work done in the East Mesa area is reported elsewhere in this proceedings (Ref. 3).

III. TEST WELLS

Based on data collected for the Mesa anomaly (Ref. 4), a deep production well was drilled to 8,030 feet in 1972. A bottom hole temperature of about 400°F was measured. The initial method of completion was by hanging a slotted seven-inch liner below the 7262-foot depth. The liner was slotted at intervals opposite electrical log-determined sand horizons. At a later date, the casing was inhole perforated uphole between 6809 and 7151 feet opposite Saraband-selected sand horizons. Prior to uphole perforation, liquid temperature of about 300°F could be produced at very low flow rates. Since perforation, a liquid at substantially greater temperature and flow rate may be produced at the wellhead. Before and after perforation flow data for Mesa 6-1 are illustrated by Mathias (Ref. 5). Mesa 6-1 has provided feed for past and current desalting operations. A second well, Mesa 6-2, was drilled in 1973, and three more wells, Mesa 5-1, Mesa 8-1, and Mesa 31-1, were drilled in 1974. The last four wells were drilled to about 6000 feet. All wells are self-starting and can produce either steam and liquid or all liquid at the surface, depending upon surface-controlled back pressure.

IV. THE TEST SITE

Figure 1 shows installation of the two desalting plants at the East Mesa test site. On the left is the multistage flash (MSF) distillation plant, which was designed, constructed, and erected by the Envirogenics Company. The plant on the right is the vertical tube evaporator (VTE) distillation unit. It was designed by W. L. Badger Associates, Inc., Burns and Roe, Inc., and constructed by Aqua Chem, Inc. Both test vehicles were designed and built under contracts issued by the Office of Saline Water (now the Office of Water Research and Technology). The Bureau of Reclamation has responsibility of operating and developing the desalting test program.

V. THE MULTISTAGE FLASH PLANT

A schematic diagram of the MSF plant is outlined in Fig. 2. The unit operates on liquid fed from the nearby separator. Liquid is introduced into a flash vessel (A), where a pressure at less than saturation is maintained. A percentage of liquid is flashed, and the steam passes through an entrainment separator (to eliminate entrained liquid droplets) and on to be condensed to a distilled product. The remaining liquid in the flash vessel passes to the next vessel, where a lower ambient pressure is maintained. This procedure is performed in three vessels. System pressures are maintained by an external vacuum pump.

The unit was originally designed to function at a maximum feed rate of 1600 pounds per minute liquid at 400°F. During tests by Envirogenics Company at its Wrightsville Beach Test Facility using synthetic geothermal fields, the inlet conditions were widely varied with feed temperatures ranging from 250 to 395°F and blowdown temperatures ranging from 140 to 250°F. The unit has been operated intermittently in the Imperial Valley for one year with minimal problems. Operating at a liquid feed of 600 pounds per minute at 221°F and a final blowdown temperature of 169°F, product water was produced at a rate of about 17 pounds per minute. Average total dissolved solids (TDS) content of the product was 170 milligrams per liter (mg/l). A product quality of 28 mg/l TDS at a pH of 9.5 was produced in the first stage. The product from the second and third stages was always more saline, ranging from 85 mg/l to 360 mg/l TDS. This was due to the lower temperature operating parameters, where brine entrainment is more likely and to other hydraulic problems of operating at less than designed temperatures. These tests were performed before the uphole perforation in Mesa 6-1.

VI. THE VERTICAL TUBE EVAPORATOR PLANT

A schematic diagram (Fig. 3) has been prepared showing the vertical tube evaporator single-effect unit in the upflow mode. The VTE test vehicle has, also, installed in parallel, a three-effect VTE unit, which has been operated for only short periods to date. The single-effect unit is constructed of carbon steel with eighteen 3/4-inch, 13 gage smooth carbon steel (A-106 GrB) tubes 20 feet long.

The VTE also operates on the flash principle. Hot geothermal liquid (after separation from steam near the wellhead) flows upward through a bundle of tubes located inside the evaporator. As liquid flows through the tubes, it

flashes down to a lower temperature and pressure, thus generating vapor. At the same time, steam surrounding the tube bundles evaporates an additional quantity of vapor from the brine. As steam transfers heat to the brine, it condenses to product water. In the single effect, generated vapor is vented, and the brine blowdown goes to waste; however, in the multi-effect VTE units, these fluids are fed to the next effect and the process is repeated. Initial operations have been in the upflow mode, but later tests will be run in the down-flow mode as the equipment has been designed to be operated either way with only minor modification.

The unit has been operated over three different test periods using fluids from Mesa 6-1 after it was uphole-perforated. Fifty hours of intermittent operation were logged over a period of one year. The vapor head was then removed for inspection. An analysis of material taken from within the tubes showed it to be an iron corrosion product with no evidence of scale deposit. The unit was cleaned with a 20 percent inhibited hydrochloric acid solution and operated on a continuous basis for 100 hours. The first 76 hours of operation were not extremely stable due to minor control problems. The last 24 hours of operation were steady with a ΔT of 23°F. Liquid entering the tubes was sub-cooled, and a heat transfer coefficient of 221 Btu/hr-ft²-°F was calculated using a log mean-temperature difference. This value was raised to 241 Btu/hr-ft²-°F by increased venting. It is, therefore, possible that excess noncondensable gases were present in the shell side of the unit.

After a 100-hour continuous run, the evaporator head was removed. Inspection revealed a small amount of corrosion product within the tubing, but no scaling was discernible. The unit was then started for a continuous test run of several hundred hours. After operating for 800 hours with only a few hours of shut-down time for instrument calibration, the trend of heat transfer coefficient values had not decreased noticeably. ΔT was increased in an attempt to promote scaling, but buildup was not evident from the data. A partial outline of operating conditions for both the 100-hour test and the long-term test is presented in Table 1.

VII. WATER CHEMISTRY

A chemist and laboratory are maintained at the East Mesa site for all geothermal-associated chemical work. A consistent technique of fluid sampling has been employed in the Bureau's geothermal work. Samples are collected by jetting the sampled fluid in neutral, basic, and acidic ice water solutions. This method prevents the precipitation of soluble components, such as silica, bicarbonate, iron, etc., that precipitate under cooling.

The water chemistry has been seen to vary at the wellhead. At high flow rates, during downhole flashing, less silica and bicarbonate are seen at the wellhead than at low flow (liquid at the surface) conditions (Ref. 5). During the long-term VTE operations, well flow rate remained constant; therefore, little changes in wellhead chemistry were evident.

A brief summary of water chemistry from the steady-state portion of the VTE single-effect 100-hour test run is illustrated in Fig. 4. It is interesting to note the trends of TDS, pH, and alkalinity as fluids are passed from the

wellhead through the system. TDS increases slightly from the wellhead to the separator outlet to the brine blowdown as would be expected due to liquid concentration as vapor is generated. The TDS of less than 10 mg/l of condensate water is not a true measure of VTE system efficiencies, but a measure of the wellhead separator efficiency. At this time, an analysis of generated vapor has not been made.

The pH measurement shows an increasing trend from the wellhead to the brine blowdown. This is due to evolution of CO_2 from waters in the separator and VTE as pressures are reduced. The condensate water pH of 6.6 suggests that steam from the separator carried an amount of CO_2 .

Alkalinity is shown in terms of equivalent parts of CaCO_3 . A decrease in alkalinity from wellhead to brine blowdown implies that CO_2 is being evolved at both the separator and VTE. The high alkalinity of condensate water is again an indication that CO_2 was transported with steam from the separator. This high alkalinity would soon drop significantly if the water were aerated or allowed to stand for a period of time.

VIII. SUMMARY

The Bureau of Reclamation has successfully operated a multistage flash-type distillation unit and a vertical tube evaporator-type distillation unit on geothermal fluids. The MSF unit has operated satisfactorily at intermittent service for over one year with low-temperature liquids and should operate more efficiently on higher-temperature liquids now available. The plant will be used in the overall test program to monitor scaling and corrosion in flash vessels. The single-effect vertical tube evaporator unit was operated continuously for 100 hours and intermittently for 50 hours with no detectable tubing scaling and some formation of corrosion products. The unit was recently shut down after a continuous test run of about 800 hours with the data indicating no systematic decrease in heat transfer coefficient. A nonscaling operation of the tubing is necessary in order to maintain heat transfer and thus insure the feasibility of using geothermal fluids in heat exchange applications. As the unit is constructed of carbon steel, the corrosion problem could be solved with correct application of various alloys or coatings.

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Table 1. A summary of operating conditions: vertical tube evaporator, single effect

Test series	100-hour test				Long-term test							
Feed rate, lb/hr	3,400	3,400	2,062	2,561	2,305	2,367	2,385	3,233	3,187	2,621		
Condensate, lb/hr	417	420	383	394	306	378	399	430	667	512		
Concentration factor ^a	1.07	1.07	1.23	1.18	1.15	1.19	1.20	1.15	1.27	1.24		
ΔT , °F	25.8	22.7	14.6	18.7	17.7	15.6	12.7	20.7	33.7	24.7		
Heat transfer coefficient, Btu/hr-ft ² -°F	211	241	348	280	229	320	413	275	264	273		
Test date, 1974	8-8	8-9 ^b	9-17	9-20	9-22	9-24	9-26	9-28	10-1	10-4		

^a Determined from chemical concentration.

^b Increase drip pot venting from 8-8 data.

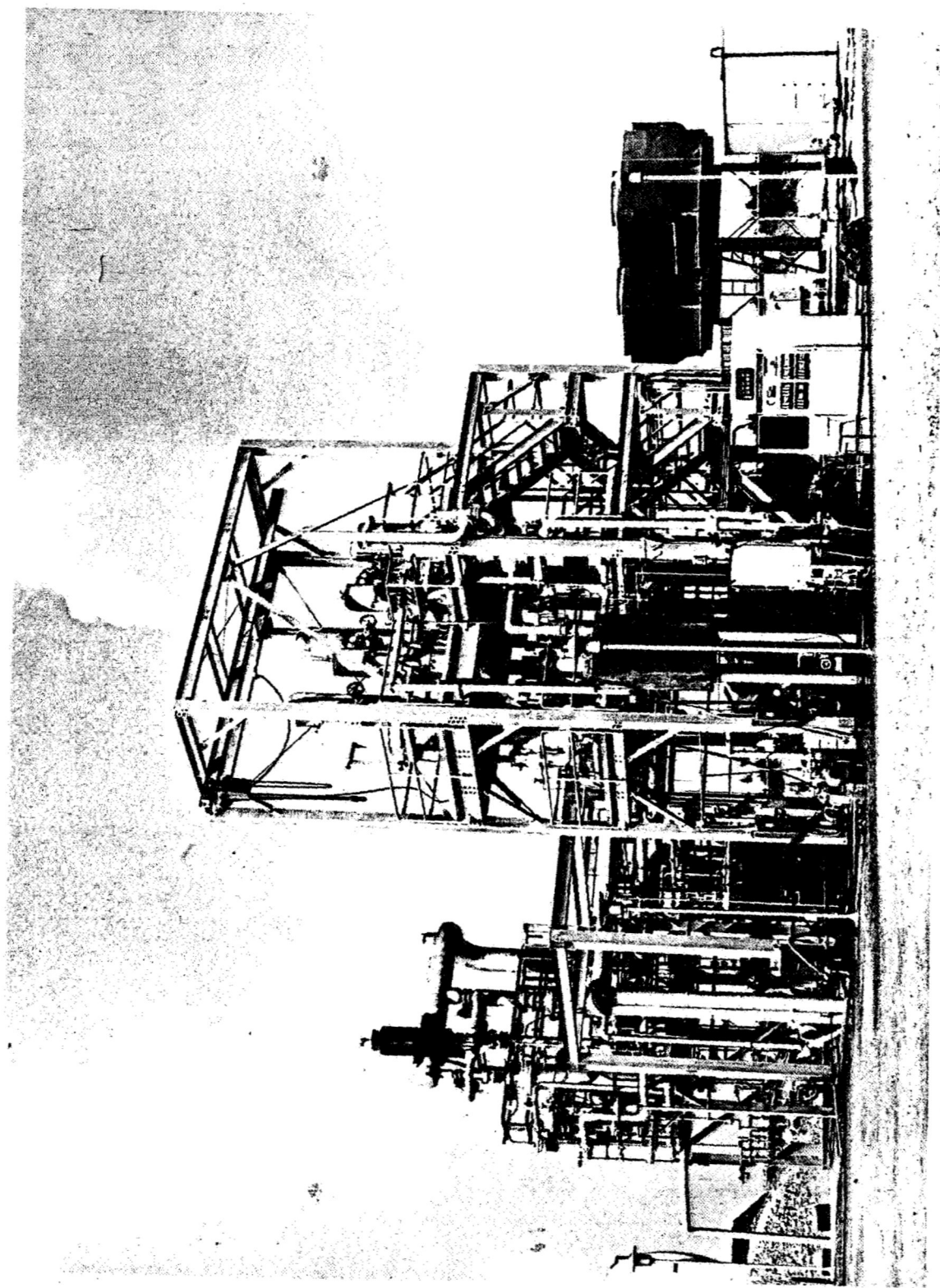


Fig. 1. Geothermal test site, Imperial Valley, California (photo by Bureau of Reclamation, U. S. Department of the Interior)

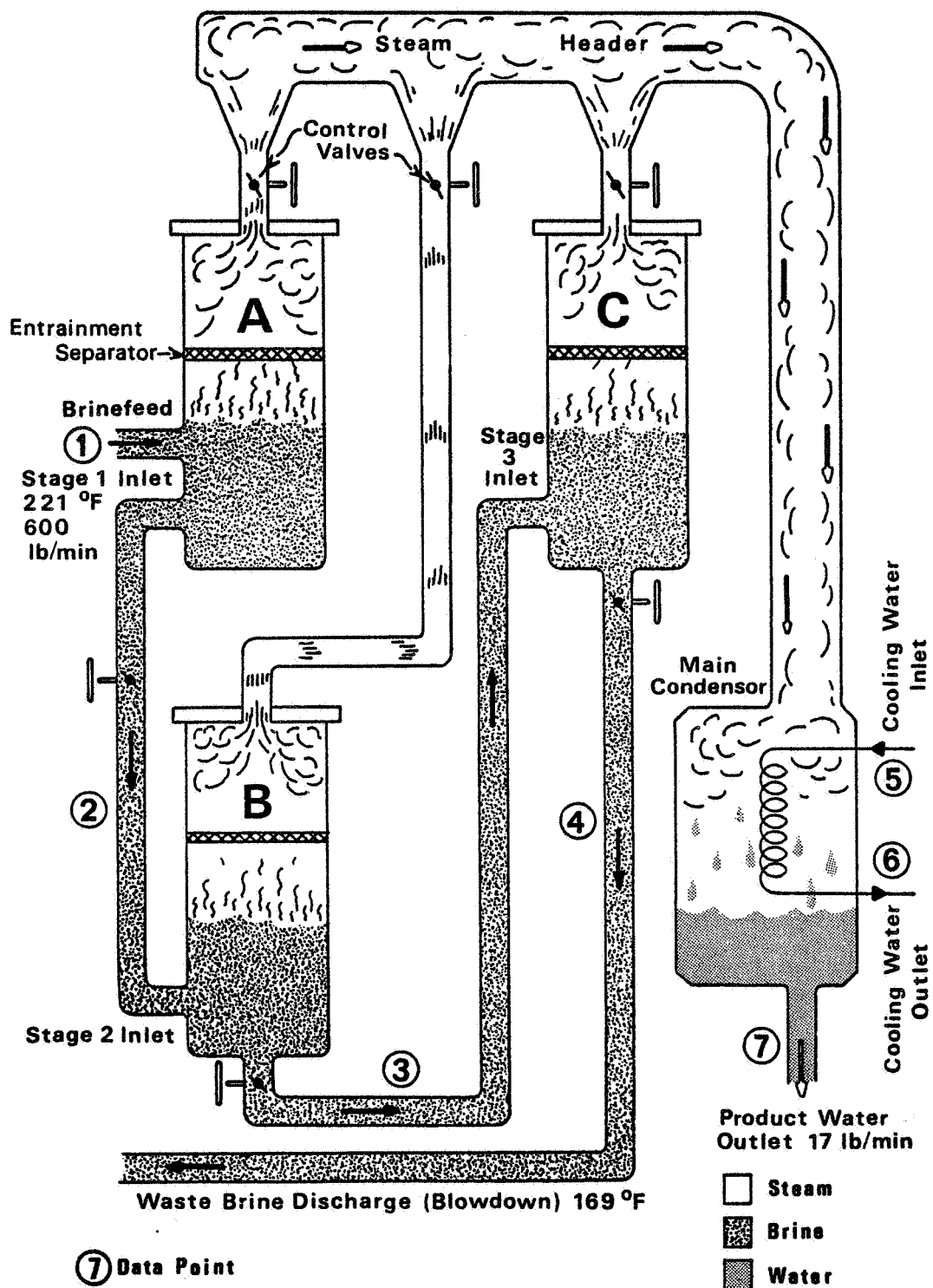


Fig. 2. Multistage flash distillation process

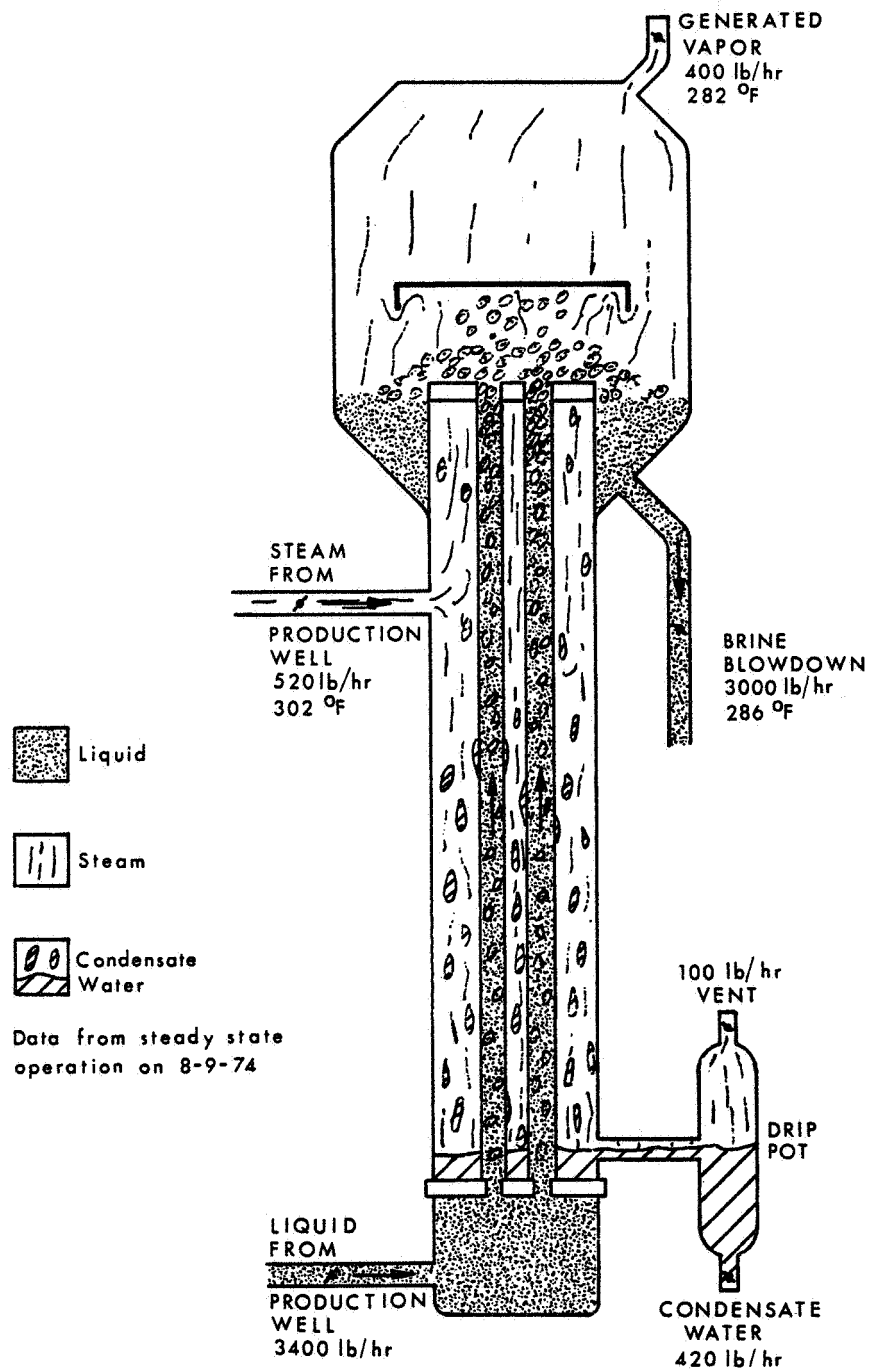


Fig. 3. Vertical tube distillation process

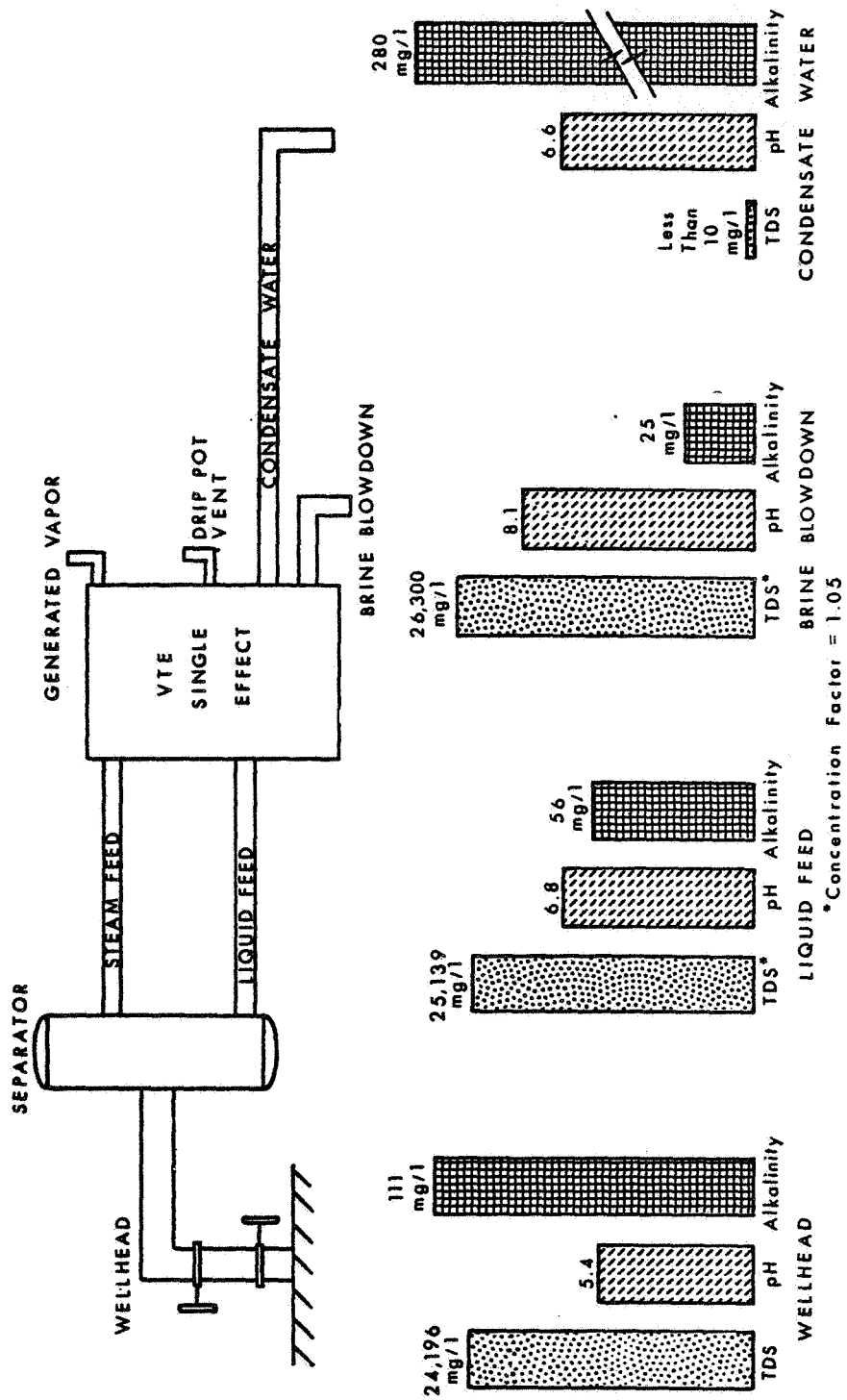


Fig. 4. Water chemistry of single-effect VTE operations

SESSION V

ADVANCED RESEARCH AND TECHNOLOGY

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SESSION V. ADVANCED RESEARCH AND TECHNOLOGY

SESSION CHAIRMAN: P. Kruger

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ROCK MELTING TECHNOLOGY AND GEOTHERMAL DRILLING

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National awareness of the potential future shortages in energy resources has heightened interest in exploration and utilization of a variety of geothermal energy (GTE) reservoirs. The status of conventional drilling of GTE wells is reviewed briefly and problem areas which lead to higher drilling costs are identified and R&D directions toward solution are suggested. In the immediate future, an expanded program of drilling in GTE formations can benefit from improvements in drilling equipment and technology normally associated with oil or gas wells. Over a longer time period, the new rock-melting drill bits being developed as a part of the Los Alamos Scientific Laboratory's Subterrene Program offer new solutions to a number of problems which frequently hamper GTE drilling, including the most basic problem - high temperature. Two of the most favorable characteristics of rock-melting penetrators are their ability to operate effectively in hot rock and produce glass linings around the hole as an integral part of the drilling process. The technical advantages to be gained by use of rock-melting penetrators are discussed in relation to the basic needs for GTE wells.

The present status of the Subterrene Program in the development of rock-melting penetrators for hard, hot rock drilling is reviewed. Extruding penetrators which condition the melt into predictable debris forms, i. e., glass rods, pellets or rock wool, have been developed and utilized in a variety of igneous and metamorphic rocks. A field test system for shallow hole experiments is being developed and the preliminary results are reviewed.

I. INTRODUCTION

This brief summary report will first review the status of geothermal well technology, which includes drilling and operational problems especially related to geothermal wells, and cost comparisons are made. This survey is a result of an extensive review of the literature and the published data. It is also the result of many personal discussions with individuals in the

various elements of the drilling and geothermal energy (GTE) industries. This survey and the detailed results and conclusions reached are contained in a report (Ref. 1) recently issued by the Los Alamos Scientific Laboratory. It is concluded that short-term improvements in current drilling technology can solve some of the problems encountered in GTE wells, especially those associated with the higher temperatures, and potentially produce significant reduction in drilling costs.

To develop and greatly expand the use of GTE in the future, new drilling methods and equipment are needed to penetrate hard, abrasive, rock and to provide hole stabilization and support at the very high temperatures and other extreme conditions which are encountered in GTE wells. The second portion of this report reviews the concepts and status of one such new technique — rock melting, indicates the status of the program to develop a prototype rock melting GTE penetration system, and indicates how such a system may solve some of the GTE well drilling problems and result in further cost reductions.

II. STATUS OF CURRENT DRILLING TECHNOLOGY

It is well established that drilling technology plays a major, often pacing, role in both the exploration (Ref. 2) and production (Ref. 3) phases of GTE reservoir development. For the purposes of this summary and to characterize the general situation, we will review the data from the two major GTE reservoirs where the majority of U. S. drilling has been conducted: The Geysers field and the Imperial Valley.

The Geysers field is characterized by:

- (1) Dry steam at 180–240°C (360–460°F) and 3400 kPa (500 psi).
- (2) Jointed, fractured, hard rock, ~50% of drilling time used to change bits.
- (3) Difficult terrain for site preparation.
- (4) Heavy duty rigs required.
- (5) Difficult well completions; use of air causes exceptional air-steam erosion.

And in the Imperial Valley:

- (1) Hot brines at 260–360°C (500–680°F) at high pressures.
- (2) Sedimentary formations.
- (3) Flat geography, accessible sites.
- (4) Smaller rigs.

The well depths are quite similar, 1.5 to 2.0 km (5000 to 6000 ft), with high temperature circulating muds (or air) required with surface heat exchangers, and elevated temperature cements used in the well casing programs. The detailed drilling conditions at these two areas are summarized in Tables 1 and 2.

The influence of these factors on costs is summarized in Fig. 1, where average total well costs in 1972 at depths of 1.5 km (~1 mile) for the two areas are compared to the average cost experience for oil and gas well drilling. We note that the cost of the Imperial Valley wells is approximately twice that of oil and gas wells, and for The Geysers field the factor is four to five. The enhanced costs in the Imperial Valley might be those associated primarily with higher temperatures and the additional increments at The Geysers are attributed to geological complications and more difficult completions. The causes of the additional cost factors for GTE drilling are therefore summarized as:

- (1) Higher temperatures.
- (2) Difficult, hard abrasive rock.
- (3) Equipment erosion from high velocity particles.
- (4) Higher rig siting costs.
- (5) Deep, longer diameter holes.

The higher temperatures are especially significant in raising drilling costs, perhaps by a factor of two as indicated above. Table 3 records the influence of the cost-raising factors as distributed across the various elements of the drilling process. This broad distribution of the problems indicates that improvement of GTE drilling will require R&D effort in all elements of the drilling system.

The above discussion centered primarily on wells in conventional GTE reservoirs where maximum depths may not exceed 3 km (10,000 ft). For projected dry hot rock and perhaps future geopressurized reservoir developments, the depths, temperatures, and drilling costs could be considerably greater. Drilling costs increase very rapidly with depth, as illustrated in Fig. 2. The cost-per-unit-depth varies about as the square of depth and total cost as the cube of depth. The average oil- and gas-well costs are shown cross hatched; typical well costs at The Geysers and Imperial Valley are shown as 160 \$/m (50 \$/ft) and 80 \$/m (25 \$/ft), respectively; for depths of 10 km (30,000 ft), costs could be \$6,000,000 to \$10,000,000 per well, assuming high temperature problems are solved.

Table 4 attempts to scope the projected GTE well drilling demands and costs (in 1972 dollars) for several proposed national geothermal energy goals. Considering several of the current goals, this analysis indicates:

- (1) That The Geysers may have $\sim \$25 \times 10^6$ invested in 92 production wells with an electrical power output of ~ 500 MWe. (We neglect exploratory holes, dry holes, etc.)

- (2) The possible numbers of wells and cost for a 20,000-MWe power production goal in the year 1985 would be ~5000 and cost a few billion dollars.
- (3) If the dry hot rock technology proves feasible, and GTE development extends beyond the conventional hydrothermal reservoirs, then only ~2000 wells would be required but costs could be $\$10 \times 10^9$, since the wells will be deeper and in hard hot rock.

Another mix of future GTE resource development would require somewhat different numbers of wells, but the cost will still be several billion dollars.

It has been amply demonstrated that naturally occurring hot-water and vapor-dominated geothermal reservoirs can be penetrated by rotary drilling methods that have been developed principally for oil and gas wells. However, there are factors in geothermal fields such as high temperatures, corrosive fluid and gases, unfavorable siting situations, and often hard abrasive rocks, which combine to make the average rotary-drilled geothermal wells more expensive than average oil and gas wells of comparable depth. High well costs could significantly impede the expansion of geothermal energy sources to a level where they will contribute substantially to our national energy supply.

III. ROCK MELTING TECHNOLOGY — POTENTIAL APPLICATIONS TO GTE WELLS

Rock-melting penetrators (Subterrenes) are under development at the Los Alamos Scientific Laboratory (Refs. 4 and 5). These devices can produce self-supporting glass-lined holes in rock and soil by progressively melting with a nonrotating, electrically heated bit, rather than by chipping, abrading, or spalling. Rocks and soils melt at temperatures that are relatively high, e.g., common igneous rock melts at ~1500 K, almost the melting temperature of steel (1500 to 1800 K). Thus, the melting penetrators utilize refractory metals such as molybdenum and tungsten in their construction.

Excavation by rock- and soil-melting offers potentially desirable and integrated solutions to the three major areas of the excavation process:

- (1) Forming the hole.
- (2) Providing stability and structural support.
- (3) Forming and removing or displacing the debris or cuttings.

The liquid form of the rock-melt produced by the hot penetrator introduces new solution approaches into the latter two areas especially:

- (1) The liquid melt can be formed and chilled into a glass lining to seal/support the borehole walls.

- (2) Excess liquid melt can be chilled and formed into glass rods, glass pellets or rock wool, as suited to an optimized debris removal system.
- (3) Glass cased cores can be formed and removed by wire line techniques.

The development program has already demonstrated a variety of melting configurations (Refs. 6 and 7) and debris handling options (see Fig. 3). Both laboratory experiments and a field test program have demonstrated the basic feasibility of the rock-melting approach.

Potential applications of Subterrene drilling systems for making geothermal wells are summarized in Table 5. The four major types of geothermal reservoirs are listed and the two basic well functions, exploratory and production, are indicated. In exploration and currently urgent resource assessments, rock melting devices could make small diameter, shallow, self-cased holes for thermal gradient measurements. Subterrenes could also be useful for economical exploration of deep hot water or steam reservoirs where very high formation temperatures prevail. For production wells there are two specialized backup or auxiliary devices that could be used in conjunction with rotary drilling systems: first, a hole-stabilization tool for use in caving formations, hydrating or swelling clays, or lost-circulation zones. This tool would be a thermal device producing either a rock-glass lining or injecting structural stabilizing materials into borehole walls. Second, a tool that would be used for completing holes into production zones where high formation temperatures and hot fluids are encountered and where reservoir contamination is undesirable. In certain deep, very hot water or steam reservoirs, or in magmas and lavas that are extremely difficult or impossible to penetrate with rotary drills, Subterrene systems could be developed for the formation of entire production wells.

The present technical activities of the Los Alamos rock-melting project that are directed toward the development of a GTE drilling system are:

- (1) Demonstrate the ability to penetrate hard dense rock, reliably in the field.
- (2) Improve advance rates of extruding penetrators.
- (3) Develop system models of deep, rock-melting drilling systems for analysis and optimization.

The first objective is being pursued through a field test operation (see Fig. 4). Testing has concentrated on an extruding penetration design of 84-mm (3-1/4 in.) diameter (see Fig. 5). A hole ~20-m (65-ft) deep has been produced in a dense, basalt layer. The tests to date have yielded data on bit life (erosion and corrosion of the penetrator), evolved improved methods for hot debris (pellets and rock wool) handling, improved glass lining-forming techniques, and developed reliable, semiautomatic rig operating methods.

A major development project to perfect a prototype GTE rock-melting well drilling system has been initiated. Larger diameter, higher advance rate, extruding penetrators have been designed and laboratory tests indicate a three-fold improvement can be achieved. A new electrical heating concept, in which a portion of the power is deposited in the melt layer, is under development.

Theoretical models for the thermal design and the fluid mechanics, electrical, structural, mechanical and economic aspects of a deep drilling system are being developed. A proof-of-concept R&D project which includes melting into a lava lake, tests of prototype hole forming and debris handling components in a high pressure, a high temperature laboratory simulator, and final system field tests in hard rock have been initiated.

IV. CONCLUSIONS

The current demands for the drilling of geothermal energy wells can be met with current oil and gas drilling technology. However, the combinations of GTE conditions of temperature, pressure, hard fractured rock, and corrosion raise the cost of average geothermal wells two to five times above the equally deep oil and gas wells. An expanded and accelerated GTE development effort can benefit from improvements in drilling technology which will lower costs.

Short-term improvements in current drilling equipment should include:

- (1) Establishment of a drilling system R&D facility and institute.
- (2) Development of a standardized line of rigs dedicated to GTE well drilling and especially designed to solve the problems particular to such drilling.
- (3) Longer lifetimes for bit cutting edges and bearings.
- (4) Stem and casing materials that can stand up to GTE well temperatures and corrosive conditions.
- (5) Muds and cements able to withstand high temperatures.
- (6) Better methods to measure downhole temperature, pressure, porosity, permeability, fracture orientation, and general formation lithology; means of obtaining undisturbed fluid samples; and measurement/sampling techniques that do not delay the drilling operations.

Longer term R&D on new drilling methods and advanced drilling technologies can potentially pay off in a greatly expanded national GTE development program. Future exploration and extraction efforts for other minerals and fuels will also benefit from successful development of advanced drilling systems. Rock melting technology may provide one such significant advancement, especially in affording penetration into deeper, very hot GTE formations and reservoirs.

ACKNOWLEDGMENT

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*Copies of these reports are available from: National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22151

Table 1. Geothermal drilling at the Geysers

Resource:	Dry steam at 180 to 240°C and 3400 kPa.
Geology:	Igneous, badly jointed and fractured.
Surface:	Mountainous terrain.
Rig sizes and power:	Extra heavy duty and power.
Hole sizes and casings:	500-mm (20-in.) conductor pipe, 445-mm (17-1/2-in.) surface hole, 311-mm (12-1/4-in.) to steam, 216-mm (8-1/2-in.) open to T.D. Buttress connections. 200- to 3000-m depths. High temperature cement required.
Circulation:	High temperature mud in upper hole, air to T.D. Exceptional air/steam erosion of equipment. Excessive lost circulation.
Drillability:	Initial: 15 m/h. Depth: 5 m/h. Temperature, fatigue, and corrosion leads to bearing failures. Average bit life extends from 45- to 75-m lengths. Approximately 50% time used to change bits.
Logging:	Up to ~temperature limits of ~260°C.
Completion:	Heavy equipment needed because of erosion.

Table 2. Geothermal drilling in Imperial Valley

Resources:	Hot brines at 260–360°C and high pressures.
Geology:	Sedimentary to 2.4- to 6.0-km depths.
Surface:	Accessible, flat.
Rig sizes and power:	Smaller, portable rigs are satisfactory.
Hole sizes and casings:	500-mm (20-in.) conductor pipe, 445-mm (17-1/2-in.) surface hole, 270-mm (10-5/7-in.) to T.D. 300- to 2100-m depths. High temperature cement required.
Circulation:	High temperature mud required. Some lost circulation but not a significant problem. 90°C mud cooled 20°C in cooling tower.
Drillability:	High rates, e.g., 15 m/h. Low bit costs.
Logging:	Up to equipment limits of 260°C.
Completion:	Simple: log, install valve, wash.

Table 3. Summary of current geothermal drilling problems

Item	Type of GTE field		Symbols and problem descriptions
	Sedimentary hot water	Hard, igneous vapor dominated	
Surface locations	—	G	G: Difficult geological conditions typical of many GTE fields, including sites, hard rocks, caving formations, etc.
Drilling-rig design	R, X	R, G, X	R: Rigs of high mobility are needed, adequately equipped to handle rapid changes in hole conditions.
Other surface equipment	T, C, X	T, C, E, X	X: Dependence on oil- and gas-industry materials and equipment, competition for supplies.
Bits and drillability	T, C, D, X	G, T, C, D, X	T: Temperatures up to ~660 K cause rubber, elastomer, metallurgical, mud, cement, and electronic problems.
Mud-circulation systems	T, G, F, X	T, G, F, X	C: Corrosion problems caused by ground fluids and gases.
Hole support and control	G, T, F	G, T, F	E: High stem, casing, and surface-equipment erosion by air + steam + rock cuttings.
Cements	T, X	T, X	D: Directional drilling equipment not available for hard rock at high temperatures.
Downhole measurements	T, X	T, X	F: Hot saline waters contaminate drilling muds. Also, muds can reduce or kill well productivity or may hydrate clays.

Table 3. Summary of current geothermal drilling problems (contd)

Item	Type of GTE field		Symbols and problem descriptions
	Sedimentary hot water	Hard, igneous vapor Dominated	
Tubular goods	T, C, X	T, C, X	0: Lack of organized GTE well drilling-data bank and ways to use such data to optimize drilling programs.
Optimized drilling	0	0	

Table 4. Projected GTE drilling costs for electric power development in U. S.

Total power goal, MW(e)	Conventional steam systems		Dry hot rock systems	
	Number of holes	Cost, \$ $\times 10^{-9}$	Number of holes	Cost, \$ $\times 10^{-9}$
412	92	0.023	—	—
20,000 ^a	4,460	1.1	1,600	10.3
200,000 ^b	44,600	11.0	16,000	103.0
400,000 ^c	85,200	22.0	32,000	206.0

^aAEC goal for 1985.

^bAEC goal for 2000.

^cHickel, 1972.

Table 5. Potential subterranean geothermal well applications

Well function	General requirements	Types of Geothermal field			
		Water or vapor-dominated reservoir	Dry-hot-rock systems	Magmas and lavas	Geopressurized reservoirs
E X P L O R A T I O N	Small and economical.	Thermal-gradient holes.	Thermal-gradient holes.	Thermal-gradient holes.	
	Directionally controllable.	Heat anomaly probes.		Heat anomaly probes.	
	Formation evaluation capability.	Discovery wells.			
	Holes enlarge-able to production size, if desired.				
P R O D U C T I O N	Large enough to achieve optimum production flow rates.	Special hole-stabilization tool, backup to rotary drills.	Special hole-stabilization tool, backup to rotary drills.	Special hole-stabilization tool, backup to rotary drills.	Special hole-stabilization tool, backup to rotary drills.
	Directionally controllable.	Production wells.	Hole-completion tool in very hot rocks.	Production wells in very hot rocks.	Hole-completion tool in very hot rocks.
	Hole made can be reworked and maintained.	Reinjection disposal holes.		Production wells in molten rocks.	
		Production-augmentation holes.			

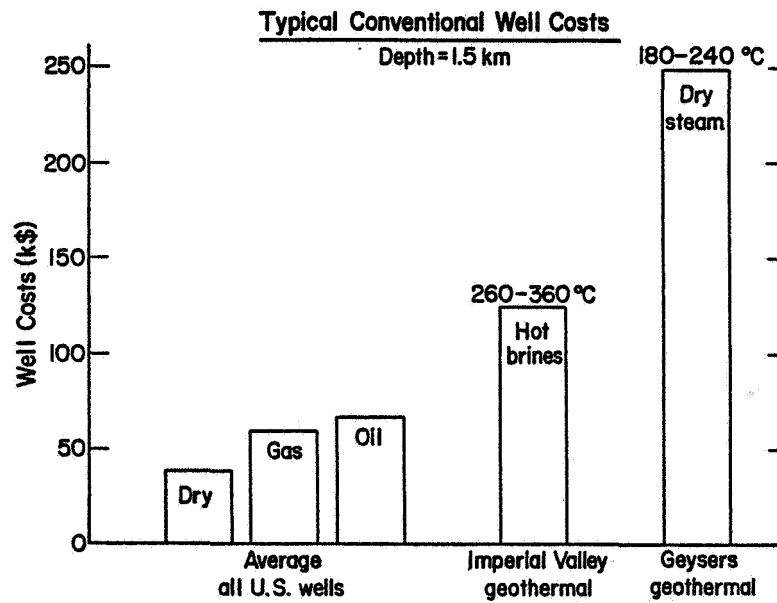


Fig. 1. Cost comparison of typical average GTE well drilling to comparable oil and gas well drilling (1972 dollars)

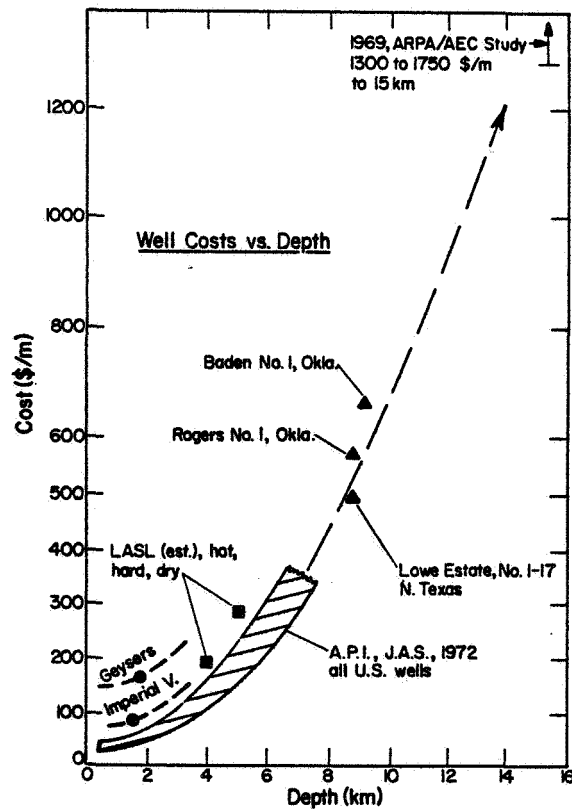


Fig. 2. Well drilling costs vs depth

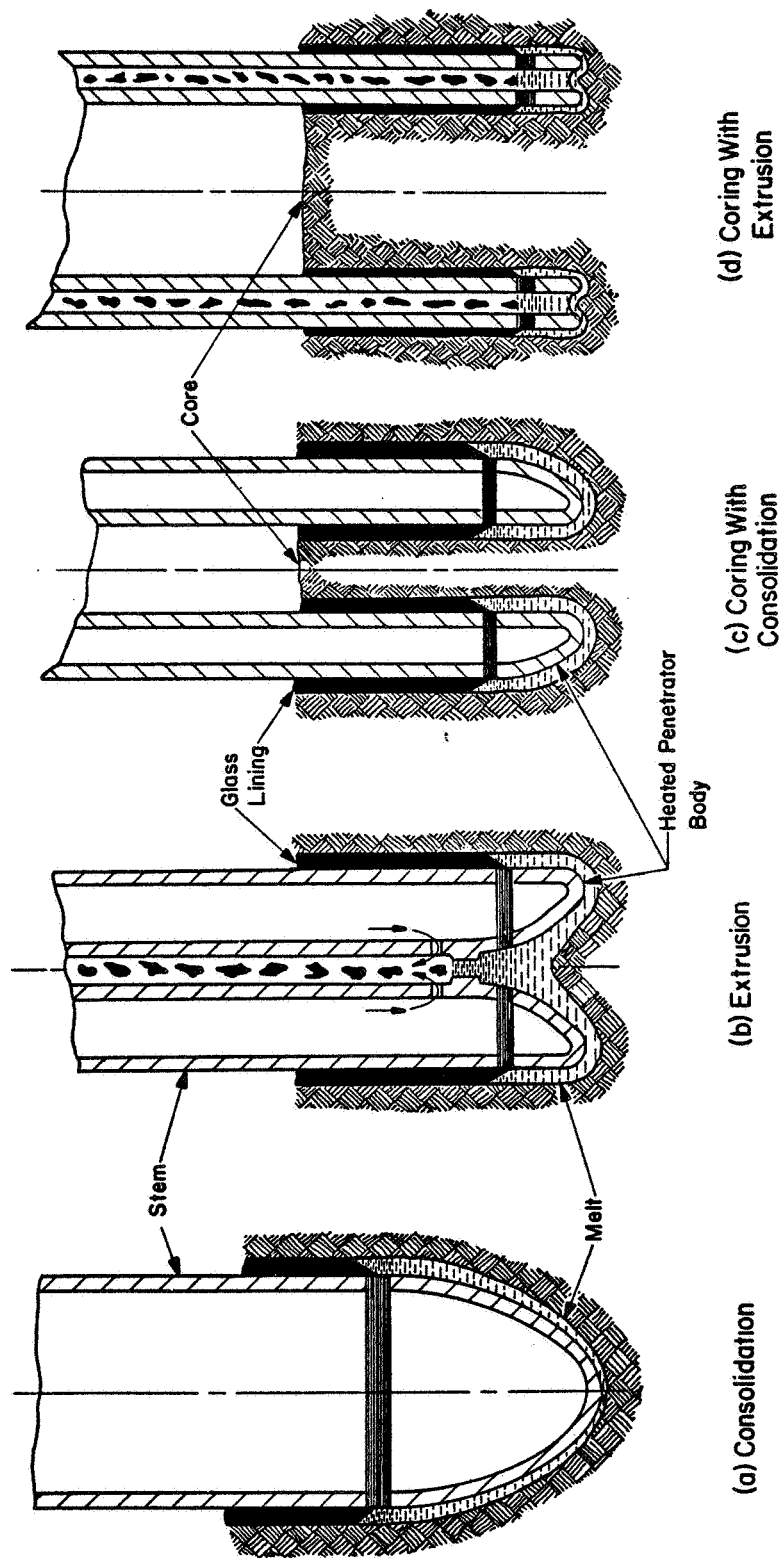


Fig. 3. Schematic cross sections of rock-melting penetrators indicating different melting modes and debris handling techniques

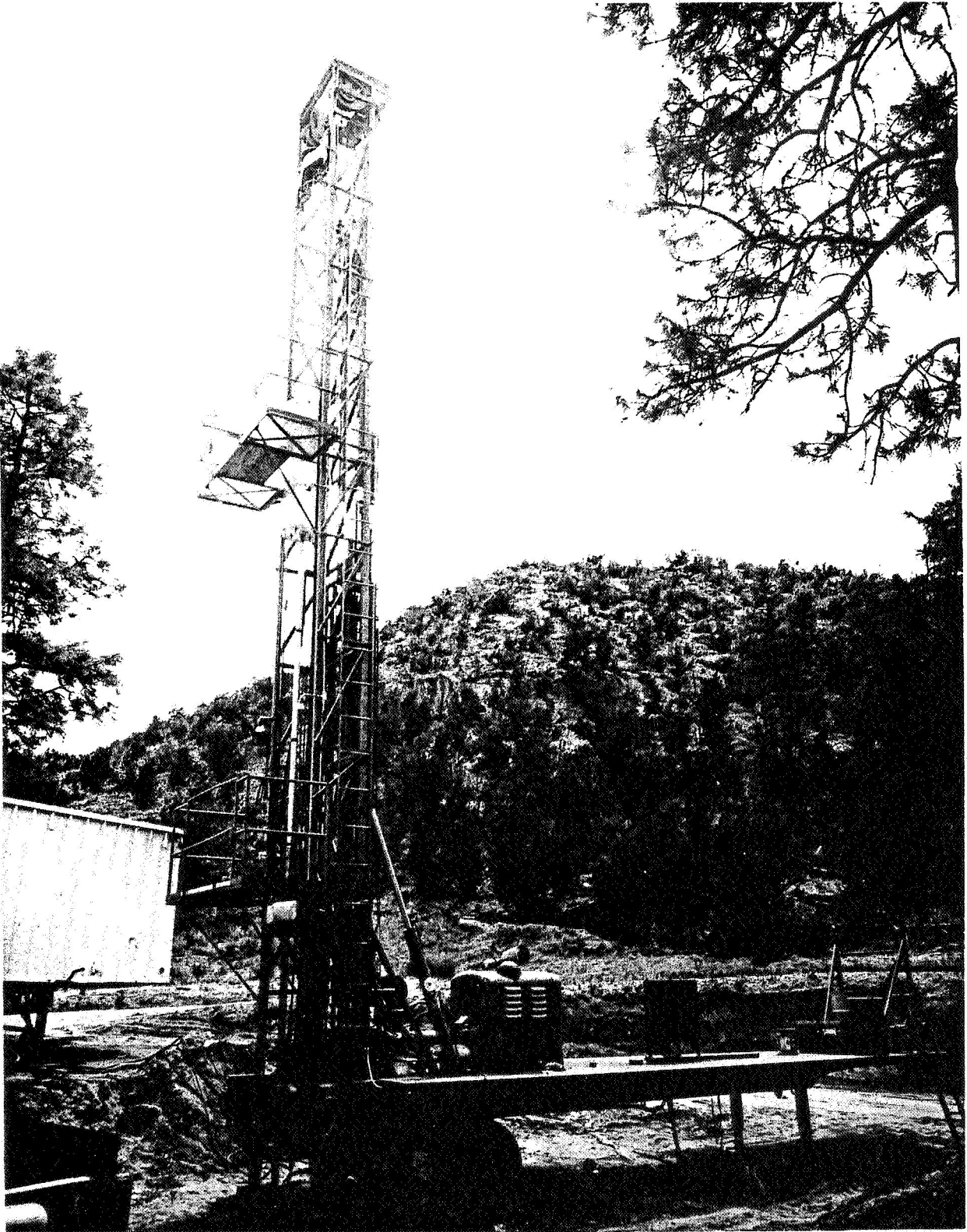


Fig. 4. Photograph of experimental field unit for test of prototype GTE rock melting penetrators, depth capability to ~300 m (1000 ft)



Fig. 5. Prototype GTE rock melting, extruding penetrator system, 84-mm (3-1/4-in.) diameter, currently undergoing field tests in basalt to ~30 m (100 ft)

GEOTHERMAL RESERVOIR SIMULATION

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The prediction of long-term geothermal reservoir performance and the environmental impact of exploiting this resource are two important problems associated with the utilization of geothermal energy for power production. Our research effort addresses these problems through numerical simulation. Computer codes based on the solution of partial-differential equations using finite-element techniques are being prepared to simulate multiphase energy transport, energy transport in fractured porous reservoirs, well bore phenomena, and subsidence.

I. INTRODUCTION

Geothermal reservoir simulation, in general, refers to reproducing and predicting the behavior of a geothermal reservoir by use of a model. In this discussion we consider only mathematical models which we define as: (1) a set of equations that describe the physical processes active in a geothermal reservoir, and (2) the solution of these equations subject to boundary and initial conditions. Because of the complex nature of the equations and boundary conditions, the solution generally involves numerical techniques in conjunction with the digital computer.

One simulates a geothermal reservoir to estimate the quantity of recoverable energy and the rate at which mass and energy may be extracted. To achieve these objectives, known geological information obtained from both surface techniques and drilling is utilized to determine equation parameters, boundary, and initial conditions. During the earlier stages of field development, this information is limited, and the simulation model will undoubtedly be crude. Through the simulation of a variety of producing schemes, however, the energy available and its rate of extraction may be roughly estimated. If the decision is made to develop the field further, the reservoir model may be used to help answer such engineering questions as optimal well location and spacing, or whether or not to reinject condensate. As more geological information becomes available through continued drilling, the simulation model may be updated to give a more accurate analysis of the geothermal reservoir.

A. Previous Investigation

The literature on the simulation of both heat and fluid flow in porous media is extensive. Much of the literature is concerned with the extraction of petroleum by in situ combustion or hot-fluid injection (e.g., Refs. 1 and 2). Another area of interest is that associated with free convection models (see, for example, Refs. 3 and 4). If, however, only geothermal reservoir simulation is considered, the literature is relatively limited.

Whiting and Ramey (Ref. 5) were the first to apply a reservoir model to a geothermal system. Their model allowed for two-phase (steam-water) flow, but did not take into consideration the spatial dependence of the solution (it was a lumped parameter model). Harlow and Pracht (Ref. 6) developed a single phase (hot-water) model coupled with a rock-fracture model. They attempted to demonstrate that geothermal energy could be extracted from hot dry rocks. Mercer (Ref. 7) applied a hot-water model to the Wairakei hydrothermal system. The model was limited spatially to the two horizontal dimensions and was unable to reproduce historical data past 1962 due to the formation of steam in the reservoir. Brigham and Morrow (Ref. 8), in an attempt to allow some spatial variation in their solution, developed three lumped-parameter models based on vapor liquid distribution. Toronyi (Ref. 9) developed a two-dimensional (areal or cross-section) reservoir model coupled with a wellbore model. His reservoir model allowed only two-phase flow, being restricted to the saturated-vapor pressure curve.

B. A General Simulator

The above models could be thought of as contributions toward a general model capable of completely describing the response of a reservoir to exploitation. The development of such a model constitutes the principal objective of our current research effort.

The physical properties of the fluid in a geothermal reservoir vary spatially and temporally to the extent that vertical velocities are often of the same order of magnitude as horizontal velocities. Consequently, a general model must be a distributed parameter model with the capability of three-dimensional simulation.

To answer important engineering questions, a general model must not only accommodate the transient flow of compressed hot water, steam-water mixtures, and super-heated steam, but also must allow for phase changes (see Fig. 1). Presently we are neglecting species transport and chemical reactions that may occur in the geothermal system.

Subsidence of the land surface is often encountered when large quantities of fluid are removed from subsurface reservoirs. Consequently, a general model should have the capability of forecasting the spatial and temporal distribution of subsidence resulting from geothermal development. Such a simulator must solve not only the fluid flow and energy transport equations but also the equations describing the elastic behavior of the reservoir skeleton.

The governing equations employed in reservoir simulation are generally based on the physics of flow through porous media. While this approach may hold in selected cases, there are many reservoirs that are productive only because large fractures are encountered during drilling. To simulate such a fractured reservoir, the classical continuum approach to porous media flow must be modified and extended to accommodate the influence of fracture flow.

While we are currently developing models which will include each of the important capabilities described above, we cannot herein describe all aspects of our research program. Consequently, we have elected to focus our attention on multi-phase energy transport, a topic which should be of interest to anyone contemplating the development of a geothermal reservoir simulation capability.

II. THEORETICAL DEVELOPMENT

The general governing equations consist of mass, momentum, and energy balances for each phase present in a geothermal system.

A. Mass Balance

The mass balances for steam, s, and water, w, may be written as:

$$-\frac{\partial}{\partial x_i} (\bar{v}_s \rho_s) + q_s + d_v = \frac{\partial(\phi S_s \rho_s)}{\partial t} \quad (1)$$

and

$$-\frac{\partial}{\partial x_i} (\bar{v}_w \rho_w) + q_w - d_v = \frac{\partial(\phi S_w \rho_w)}{\partial t} \quad (2)$$

where

\bar{v} = phase average velocity, $[Lt^{-1}]$

ρ = average density, $[ML^{-3}]$

q = source term, $[ML^{-3}t^{-1}]$

d_v = rate of vaporization, $[ML^{-3}t^{-1}]$

ϕ = porosity, dimensionless

S = saturation, dimensionless, where $S_w + S_s = 1$

B. Momentum Balance

For velocity, we assume that Darcy's equation for multiphase flow may be used (see Ref. 10):

$$\bar{v}_s = - \frac{\bar{k}k_{rs}}{\mu_s} \left(\frac{\partial p_s}{\partial x_j} - \rho_s \bar{g} \right) \quad (3)$$

and

$$\bar{v}_w = - \frac{\bar{k}k_{rw}}{\mu_w} \left(\frac{\partial p_w}{\partial x_j} - \rho_w \bar{g} \right) \quad (4)$$

where

\bar{k} = local intrinsic permeability tensor, $[L^2]$

k_r = relative permeability, dimensionless

μ = dynamic viscosity, $[ML^{-1}t^{-1}]$

p = pressure, $[ML^{-1}t^{-2}]$

\bar{g} = gravitational acceleration, $[Lt^{-2}]$

Combining Eqs. (1) with (3) and (2) with (4) gives

$$\frac{\partial}{\partial x_i} \left\{ \frac{\bar{k}k_{rs}\rho_s}{\mu_s} \left(\frac{\partial p_s}{\partial x_j} - \rho_s \bar{g} \right) \right\} + q_s + d_v = \frac{\partial}{\partial t} (\phi S_s \rho_s) \quad (5)$$

and

$$\frac{\partial}{\partial x_i} \left\{ \frac{\bar{k}k_{rw}\rho_w}{\mu_w} \left(\frac{\partial p_w}{\partial x_j} - \rho_w \bar{g} \right) \right\} + q_w - d_v = \frac{\partial}{\partial t} (\phi S_w \rho_w) \quad (6)$$

These equations describe the flow of steam and water in a porous medium where a pressure difference exists between the two phases. This pressure difference is generally defined as capillary pressure, p_c , where

$$p_c = p_s - p_w \quad (7)$$

Probably the most important effect that capillary pressure has in a geothermal reservoir is to lower the vapor-pressure curve. Ramey, et al. (Ref. 11) point out that the reason for the lowering of the vapor-pressure curve is that vapor-pressure data found in steam tables (Refs. 12 and 13) are based on flat steam-water interfaces, whereas capillary pressure causes the interface in porous media to be curved. The amount the vapor-pressure curve is lowered in a geothermal reservoir is not completely understood. The work of Calhoun, et al. (Ref. 14), on consolidated rock does show a lowering of the vapor-pressure curve with decreased fluid saturation. The efforts of Cady (Ref. 15) and Bilhartz (Ref. 16), however, indicate no significant vapor pressure lowering in their experiments using unconsolidated sands. An important difference in the two results is that the experiments of Calhoun, et al., were made at a temperature of 36°C, and those conducted by Cady and Bilhartz ranged from approximately 121 to 240°C. Further work on the importance of capillary pressure in geothermal reservoirs is required. In this paper, capillary pressure is assumed to be negligible. Under this assumption Eqs. (5) and (6) combine to reduce the number of equations and unknown parameters by one:

$$\frac{\partial}{\partial x_i} \left\{ \frac{\bar{k}k_{rs}\rho_s}{\mu_s} \left(\frac{\partial p}{\partial x_j} - \rho_s \bar{g} \right) \right\} + \frac{\partial}{\partial x_i} \left\{ \frac{\bar{k}k_{rw}\rho_w}{\mu_w} \left(\frac{\partial p}{\partial x_j} - \rho_w \bar{g} \right) \right\} + q_s + q_w = \frac{\partial(\phi\rho)}{\partial t} \quad (8)$$

where ρ is the density of the total steam water mixture, defined as:

$$\rho = \rho_s S_s + \rho_w S_w \quad (9)$$

Note that in combining Eqs. (5) and (6) the vaporization term, d_v , has also been eliminated.

C. Energy Balance

Three energy balances, analogous to the mass balances written for steam and water, can be written for steam, water, and rock. If it is assumed that the movement of fluid (water and steam) through porous media is sufficiently slow, and the surface areas of all phases concerned are sufficiently large, then thermal equilibrium exists between the rock, steam, and water. This assumption reduces the three energy-balance equations to the following one:

$$\begin{aligned}
& - \frac{\partial}{\partial x_i} (\bar{v}_s \rho_s h_s + \bar{v}_w \rho_w h_w) + q_w h_w + q_s h_s + \frac{\partial}{\partial x_i} \left(\bar{K}_m \frac{\partial T}{\partial x_j} \right) \\
& = \frac{\partial}{\partial t} [\phi \rho h + (1 - \phi) \rho_r h_r] - \frac{Dp^*}{Dt}
\end{aligned} \tag{10}$$

where

$$\frac{Dp^*}{Dt} = \frac{\partial \phi p}{\partial t} + (\bar{v}_s + \bar{v}_w) \frac{\partial p}{\partial x_i} \tag{11}$$

The term described by Eq. (11) represents the compressible work term, and is often assumed negligible and omitted from the energy balance. Other definitions of terms in Eq. (10) include:

- h_s = enthalpy of saturated steam, $[L^2 t^{-2}]$
- h_w = enthalpy of saturated water, $[L^2 t^{-2}]$
- T = temperature, $[T]$
- \bar{K}_m = thermal dispersion tensor for the medium $[MLt^{-3}T^{-1}]$
- ρ_r = average rock density, $[ML^{-3}]$
- h_r = rock enthalpy, $[L^2 t^{-2}]$
- h = total enthalpy of the mixture, as defined by

$$h = \frac{S_s \rho_s h_s + S_w \rho_w h_w}{\rho} \tag{12}$$

D. Assumptions

By making the assumptions of thermal equilibrium and negligible capillary pressure, we are left with two equations. We must obtain additional relationships for the remaining dependent variables as functions of these two.

The two dependent variables specified as unknowns must uniquely define the thermodynamic state of the system. Further, it is desirable that these variables be commonly measured in a field situation. For these reasons, we

choose to put Eqs. (8) and (10) in terms of the dependent variables h , the total enthalpy of the mixture, and p , the fluid pressure. To do this we make the following assumptions:

- (1) Porosity, ϕ , is a function of pressure alone.
- (2) Rock density, ρ_r , may be treated as constant.
- (3) Total density, ρ , steam density, ρ_s , and water density, ρ_w , are considered functions of pressure and enthalpy.
- (4) Steam enthalpy, h_s , and water enthalpy, h_w , can be treated as functions of pressure.
- (5) Temperature, T , can be treated as a function of pressure in the two-phase region, and can be treated as a function of pressure and enthalpy in the single-phase region.
- (6) Rock enthalpy, h_r , can be considered as a function of temperature.
- (7) Viscosities, μ_s and μ_w , are considered functions of temperature.
- (8) Saturations, S_w and S_s , are functions of enthalpy and pressure.
- (9) Relative permeability can be treated as a function of saturation alone and relationships similar to those in Brooks and Corey (Ref. 17) may be used.
- (10) Thermal dispersion tensor can be generalized and treated as a property of the medium.

Ramey, et al. (Ref. 18), point out that relative permeability can also be a function of temperature. Using unconsolidated sand and working with oil and water, Poston, et al. (Ref. 19), observed that for increased temperatures, the relative permeability curves shift to the left on the saturation axis. Regarding the thermal dispersion tensor it should be noted that Mercer (Ref. 7) separates the medium thermal dispersion tensor into three parts: conduction in the solid phase, diffusion in the liquid phase, and a velocity-dependent dispersion in the liquid phase. Further, Somerton, et al. (Ref. 20), point out that the thermal conductivity of the medium is a function of temperature, porosity, and water saturation.

E. Final Equations

Making the above assumptions, Eqs. (8) and (10) become:

$$\begin{aligned}
 & \frac{\partial}{\partial x_i} \left\{ \frac{\bar{k}_{rs} \rho_s}{\mu_s} \left(\frac{\partial p}{\partial x_j} - \rho_s \bar{g} \right) \right\} \\
 & + \frac{\partial}{\partial x_i} \left\{ \frac{\bar{k}_{rw} \rho_w}{\mu_w} \left(\frac{\partial p}{\partial x_j} - \rho_w \bar{g} \right) \right\} \\
 & + q_s + q_w = \left\{ \rho \frac{d\phi}{dp} + \phi \left(\frac{\partial \rho}{\partial p} \right)_h \right\} \frac{\partial p}{\partial t} + \phi \left(\frac{\partial \rho}{\partial h} \right)_p \frac{\partial h}{\partial t} \quad (13)
 \end{aligned}$$

and

$$\begin{aligned}
 & h_s \frac{\partial}{\partial x_i} \left\{ \frac{\bar{k}_{rs} \rho_s}{\mu_s} \left(\frac{\partial p}{\partial x_j} - \rho_s \bar{g} \right) \right\} \\
 & + h_w \frac{\partial}{\partial x_i} \left\{ \frac{\bar{k}_{rw} \rho_w}{\mu_w} \left(\frac{\partial p}{\partial x_j} - \rho_w \bar{g} \right) \right\} \\
 & - \left(\bar{v}_s \rho_s \frac{dh_s}{dp} + \bar{v}_w \rho_w \frac{dh_w}{dp} \right) \frac{\partial p}{\partial x_i} \\
 & + q_w h_w + q_s h_s \\
 & + \frac{\partial}{\partial x_i} \left\{ \bar{K}_m \left[\left(\frac{\partial T}{\partial p} \right)_h \frac{\partial p}{\partial x_j} + \left(\frac{\partial T}{\partial h} \right)_p \frac{\partial h}{\partial x_j} \right] \right\} = \left\{ (\rho h - \rho_r h_r) \frac{d\phi}{dp} + \phi h \left(\frac{\partial \rho}{\partial p} \right)_h \right. \\
 & \quad \left. + (1 - \phi) \rho_r \left(\frac{\partial h_r}{\partial p} \right)_h \right\} \frac{\partial p}{\partial t} + \left\{ \phi h \left(\frac{\partial \rho}{\partial h} \right)_p \right. \\
 & \quad \left. + (1 - \phi) \rho_r \left(\frac{\partial h_r}{\partial h} \right)_p + \phi \rho \right\} \frac{\partial h}{\partial t} - \frac{Dp}{Dt} \quad (14)
 \end{aligned}$$

Equations (13) and (14) are in terms of the dependent variables enthalpy and pressure. As can be seen from Fig. 1, a pressure and enthalpy value for a given point in space will determine whether compressed hot water, a steam-water mixture or super-heated steam exists at that point. Thus, Eqs. (13) and (14) may be used to describe most types of geothermal reservoirs. To simulate the behavior of such a reservoir, however, a solution for Eqs. (13) and (14) is required.

Equations (13) and (14) are nonlinear, and their solution requires the use of numerical techniques. Such techniques are beyond the scope of this paper and will be mentioned only briefly. They include finite difference techniques, the finite element method, or some combination of the two. The nonlinear coefficients are generally handled by iteration, using, for example, the Newton-Raphson method (Refs. 2 and 9). Finally, some form of weighting of the spatially dependent variables is commonly used, upstream weighting of permeability, for example (Ref. 2).

III. CONCLUSIONS

We have presented the governing equations for energy transport and the flow of water and steam in porous media in order to provide a basis for the mathematical modeling of geothermal reservoirs. The primitive form of these equations is straightforward and available in various forms in the literature. Our objective here was to take the general mass and energy balances and reduce them to workable equations. It should be emphasized that the method described represents only one of many possible approaches. The development of a method for obtaining solutions to these equations is a challenging problem and beyond the scope of this paper.

This particular approach to geothermal modeling has been guided by several objectives: (1) the model must provide efficient and accurate solutions consistent with the available geological and hydrological data, (2) it should be applicable to hot-water, steam-water, and super-heated steam geothermal systems, and (3) the method must be easily applied to natural geothermal reservoirs. Two assumptions, peculiar to this development, were made to achieve these objectives: (1) thermal equilibrium exists between all phases, in steam, water, and rock; and (2) capillary pressure between the steam and water phases is negligible. Invoking these assumptions the basic relationships reduce to two partial differential equations written in terms of convenient field variables, fluid pressure and enthalpy. These final two equations in conjunction with well-known thermodynamic relationships provide the basis for a numerical model which we feel fulfills our initial objectives.

The suitability of this model for simulation of natural geothermal reservoirs is limited in two general ways: (1) by the validity of the basic assumptions (negligible capillary pressure, porous media, etc.), and (2) by the availability of reliable geological and hydrological and thermodynamical data for the reservoir to be simulated. Within these constraints, the suggested approach should prove useful in geothermal reservoir development and management.

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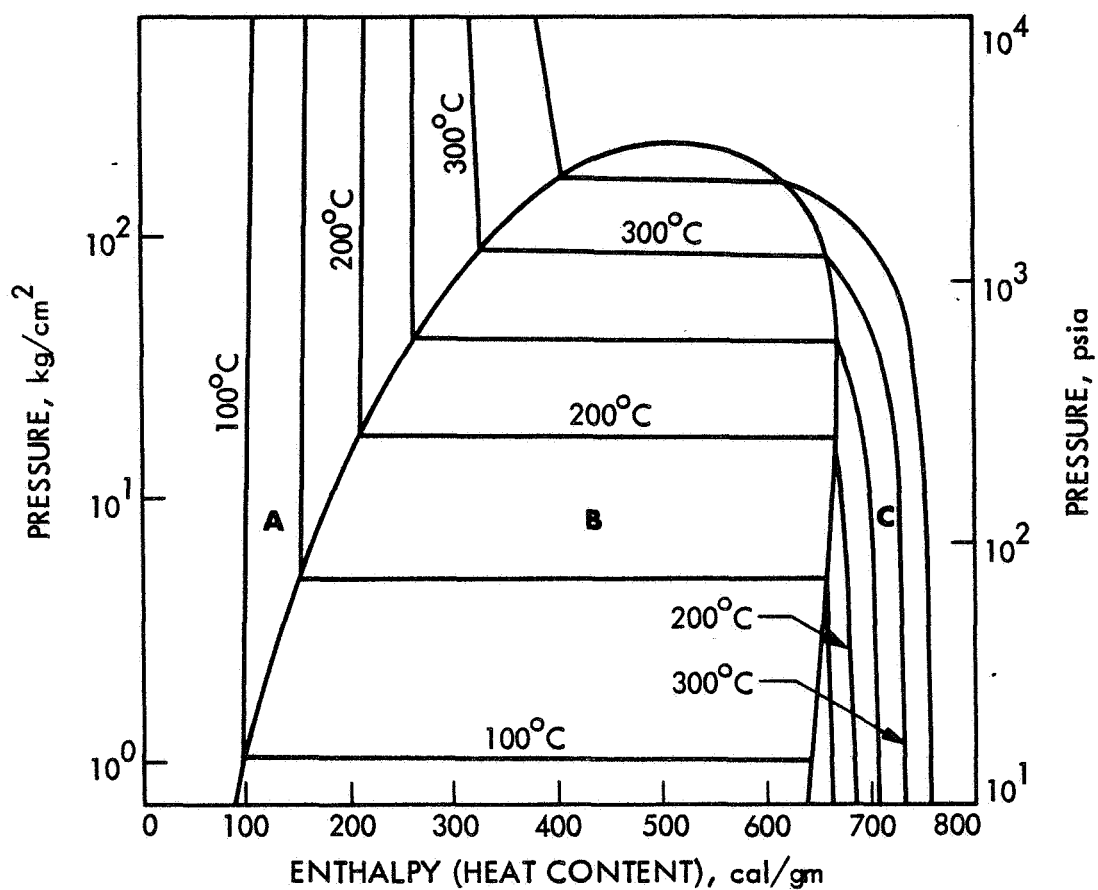


Fig. 1. Pressure-enthalpy diagram for pure water and vapor showing temperature contours (after Ref. 21). Regions are for: (A) compressed hot water, (B) steam-water mixture, and (C) super-heated steam.

GEOTHERMAL RESERVOIR ENGINEERING RESEARCH

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The Stanford University research program on the study of stimulation and reservoir engineering of geothermal resources commenced as an interdisciplinary program in September, 1972. The broad objectives of this program have been: 1) The development of experimental and computational data to evaluate the optimum performance of fracture-stimulated geothermal reservoirs; 2) the development of a geothermal reservoir model to evaluate important thermophysical, hydrodynamic, and chemical parameters based on fluid-energy-volume balances as part of standard reservoir engineering practice; and 3) the construction of a laboratory model of an explosion-produced chimney to obtain experimental data on the processes of in-place boiling, moving flash fronts, and two-phase flow in porous and fractured hydrothermal reservoirs.

During the current annual period, both the geothermal chimney model and the two-phase boiling model were essentially completed and placed into operation. Also completed was a feasibility study of the potential of naturally occurring radon as a tracer for reservoir characteristics. Experiments are being initiated in several related aspects of mass and heat transfer in fractured rock and in-place boiling in porous media. Continued effort is underway in the development of the mathematical simulation model of geothermal reservoirs.

I. INTRODUCTION

The Stanford University research program on the study of well stimulation and reservoir engineering of geothermal resources commenced as an interdisciplinary program in September, 1972. The broad objectives of this program have been:

- (1) The development of experimental and computational data to evaluate the optimum performance of fracture-stimulated wells in geothermal reservoirs.
- (2) The development of geothermal reservoir models to evaluate important thermophysical, hydrodynamic, and physical and chemical parameters based on fluid-energy-volume balances as part of standard reservoir engineering practice.

- (3) The construction of a laboratory model of an explosion-produced chimney in a well to obtain experimental data on the processes of in-place boiling, moving flash fronts, and two-phase flow in porous and fractured hydrothermal reservoirs.

The project was initiated as a joint program between the Civil Engineering Department of the School of Engineering and the Petroleum Engineering Department of the School of Earth Sciences. During the present year, assistance was provided by the Mechanical Engineering Department of the School of Engineering.

During the current annual period, both the geothermal chimney model and the two-phase boiling model were essentially completed and placed into operation. Also completed was a feasibility study of the potential of naturally occurring radon as a tracer for reservoir characteristics. Experiments are being initiated on several related aspects of mass and heat transfer in fractured rock, and in-place boiling in porous media. Continued effort is underway in the development of the mathematical simulation model of geothermal reservoirs.

Detailed results were presented at a project review to representatives from industry, university, and government agencies during May, 1974. Detailed results were presented in June, 1974 (Ref. 1), in project report SGP-TR-1.

II. THE GEOTHERMAL CHIMNEY MODEL

A description of the geothermal chimney model and an analysis of the design requirements for the major components were discussed in Progress Report No. 1 (Ref. 2). The major test objectives of the model were also described in Progress Report No. 1. In summary, the model was designed to investigate the effectiveness of fracture stimulation of geothermal wells in increasing the extraction efficiency of geothermal energy. Experimental data are being obtained on the processes of in-place boiling, moving flash fronts, and two-phase flow in porous and fractured hydrothermal media. The general problems being examined included: (1) conditions for optimum energy extraction, (2) methods of cyclic and continuous recharge, (3) determination of heat transfer characteristics, (4) water quality aspects of produced geofluids, and (5) experimental data for mathematical models of stimulated reservoirs.

Analysis of the design requirements for the chimney model indicated that a maximum design temperature of 500°F and pressure of 800 psig would be an acceptable compromise between the desire to operate at the highest pressure and temperature conditions occurring in natural geothermal reservoirs and the need to minimize the thermal capacitance of the metal in the model.

A. Description of the Chimney Model

A photograph of the chimney model on construction completion is shown in Fig. 1. Figure 2 is a schematic diagram of the chimney model system. The system operates in two primary modes: the "heating mode," which establishes the initial reservoir temperature and pressure conditions in a relatively short time, and the "fluid production mode," during which production from a fractured geothermal system is simulated.

B. Initial Experiments

Initial experiments have been conducted to measure the heatup and cool-down transients of the geothermal chimney model. Analysis was made of the heating time required to bring the water/rock/vessel system to the desired initial reservoir conditions. A simplified "lumped parameter" analysis of the problem has been made in which the various masses of rock, water, and metal are considered to be at uniform temperature.

The lumped parameter approach assumes that all of the water is at uniform temperature and that the energy received from the electric heater is distributed uniformly to each water element.

The lumped parameter approach is generally considered to be adequate when the Biot number is small, i. e.,

$$Bi = \frac{hL}{k} < 0.1 \quad (1)$$

For rocks with an equivalent diameter of 1 inch, the Biot number for typical chimney conditions is 0.8. Although the Biot number for the rock appears to be larger than 0.1, experience has shown that during the slow heating transient, the temperature difference between the water and the rock is only about 1°F.

The lumped parameter approximation for the metal sections is valid because the Biot numbers for the metal portions of the vessel in contact with water are small. The biot number for the vessel wall is 0.025.

An initial model was developed consisting of four lumped masses. Since the computer costs for the four-mass model transient runs were relatively high and it became apparent that the rock temperature was essentially the same as the water temperature for these operating conditions, a simpler two-mass model was devised for the system. The model consists of one mass for the water and rock at uniform temperature T_1 and a second mass at temperature T_2 for all of the metal in contact with hot water during the heatup process. The two simultaneous differential equations in $\theta_i = T_i - T_\infty$ are:

$$M_1 C_1 \frac{d\theta_1}{dt} + h_1 A_1 (\theta_1 - \theta_2) = S \quad (2)$$

$$M_2 C_2 \frac{d\theta_2}{dt} + h_1 A_1 (\theta_2 - \theta_1) + h_2 A_2 \theta_2 = 0 \quad (3)$$

Let

$$a_1 = \frac{h_1 A_1}{M_1 C_1}, \quad a_2 = \frac{h_1 A_1}{M_2 C_2}, \quad a_3 = \frac{h_2 A_2}{M_2 C_2}, \quad \text{and} \quad \bar{S} = S/M_1 C_1 \quad (4)$$

With initial conditions $\theta(0) = \theta(0) = 0$, and assuming constant coefficients and heat source, the solution to this problem is:

$$\theta_1 = \frac{\bar{S}(m_1 + a_2 + a_3)}{(m_1 - m_2)m_1} (e^{m_1 t} - 1) + \frac{\bar{S}(m_2 + a_2 + a_3)}{(m_2 - m_1)m_2} (e^{m_2 t} - 1) \quad (5)$$

$$\theta_2 = \frac{\bar{S} a_2}{m_1(m_1 - m_2)} (e^{m_1 t} - 1) + \frac{\bar{S} a_2}{m_2(m_2 - m_1)} (e^{m_2 t} - 1) \quad (6)$$

where the inverse time constants m_1 and m_2 are given by:

$$m_{1,2} = 1/2(a_1 + a_2 + a_3) \pm 1/2[(a_1 + a_2 + a_3)^2 - 4a_1 a_3]^{1/2} \quad (7)$$

The system parameters for this problem are $h_1 A_1 = 4500$, $h_2 A_2 = 110$, $M_1 C_1 = 630$, and $M_2 C_2 = 825$.

The heat losses from the system to its surroundings are of major importance in determining the heat transfer from the rock media. The heat transfer problem is complex due to the irregular vessel shape, various insulation thicknesses, and fin effects from valves and other noninsulated objects. Since the heat loss cannot be predicted with sufficient accuracy, an experimental approach has been used in which the system is heated to an initial high temperature. During cooling, the temperature-time history is measured at various places in the system. The effective heat transfer conductance to the surroundings can then be evaluated from the slope of the water and metal mean temperature-time data. This results from an analytic solution of the cooldown transient (Ref. 1).

Data from the first completed cooldown run (Run No. 032774) are shown in Fig. 3.

Many additional heating and cooling runs have been made, and operation of the chimney model will continue. Extension to operation with boiling brines with recharge is programmed for 1975-1976. Study of movement of flash fronts will continue, and development of a mathematical model is in progress. A study of heat transfer coefficients for fluid flow past large rock particles is also in progress.

III. BENCH-SCALE MODELS

The test objectives and apparatus involved in the bench-scale models were presented in Progress Report No. 1 (Ref. 2). In brief, these experiments were designed to test fundamental concepts for nonisothermal boiling two-phase

flow through porous media. This work is aimed at the entire reservoir, while the chimney model deals most directly with the well-bore and near-well reservoir conditions. The combination should be broadly useful in the new field of geothermal reservoir engineering.

The term "geothermal reservoir engineering" is an adaptation of "petroleum reservoir engineering," the branch of engineering which deals with assessment, and planning, of optimum development of petroleum reservoirs. Fortunately, there is much that is useful for geothermal engineering in the literature of oil recovery. Oil recovery by steam injection (Ref. 3) and underground combustion (Ref. 4) present some of the important features of nonisothermal two-phase flow which appear pertinent to geothermal reservoirs. But there has been only one specific study of the flow of single-component (water) two-phase (thus nonisothermal) flow in porous media (Ref. 5). In particular, there is no information on the important phenomena involved when normally immobile liquid saturations (practical irreducible water saturation) vaporize with pressure reduction.

The first bench-scale model planned is a steady-state flow experiment involving linear flow (in the axial direction) through a cylindrical core.

A. The Linear Flow Model

The linear flow model was described in Progress Report No. 1 (Ref. 2). All necessary components have been acquired, and fabrication of the preliminary test model has been completed. A schematic diagram of the completed apparatus is shown in Fig. 4. Two types of porous media have been used to date: a Berea sandstone core, and several synthetic consolidated sandstone cores. Fondu calcium aluminate cement, silica sand of about 100 Tyler mesh size, and water were used as the materials to make the synthetic cores. The mixture was poured into a mold formed with a plastic tubing in which a glass tubing for a liquid content probe and a thermocouple tubing were held in place. The liquid saturation probe was originally developed by Baker (Ref. 6) in connection with a study of oil recovery by injection of steam. The instrument uses the difference in dielectric constant between the liquid water and steam present in the pore space.

It was decided to run a series of basic single-phase experiments prior to performing the boiling two-phase, nonisothermal flow experiments. These included: (1) measurement of absolute permeability to gas and liquid water at a range of temperatures, (2) injection of hot water into a system containing water at a lower temperature, (3) cold water injection into a system containing hot water initially, and (4) injection of steam into a system containing liquid water at a lower temperature. Selected results are presented in Ref. 1.

Figure 5 presents temperature versus distance along the core for injection of hot water into a core initially at room temperature, as an example. Much useful information can be extracted from data such as are shown in Fig. 5. Basic information on single-phase nonisothermal flow, effective thermal conductivities in the direction of flow, and heat loss radially from the core may be found. In regard to radial heat loss, two determinations can be

of interest: (1) the thermal efficiency of the injection, and (2) the overall heat transfer coefficient for the core within the sleeve to the surroundings. Both types of evaluation have already been made successfully.

IV. LABORATORY EXPERIMENTS

During the last year, it has become apparent that several laboratory experiments should be run in parallel rather than in series if the application of research results to practical problems can be made to meet national energy objectives. For this reason, several experiments were moved up in the program time schedule. These included experiments on heat and mass transfer in porous fractured rocks and fractured nonporous rocks, and operation of geothermal reservoir models.

A. Heat and Mass Transfer in Porous and Fractured Media

Fractured porous rocks contain two types of void space: macropores, which are void volumes between rock fragments, and micropores, the pore space inside individual rock fragments. Micropores may be either natural porosity or fractures. Fluid flow through certain geothermal reservoirs is expected to occur primarily through the macropores. However, if mass transfer does take place between the water inside the micropores and potentially cooler water in the macropores, heat extraction by circulating fluids may be significant.

The study of mass transfer phenomena inside a highly fractured geothermal reservoir can be simplified by measurement of mass transfer within individual rocks. An effective means of making such studies is by addition of a tracer to the micropore water. A tracer which has proven of immense value in studies requiring chemical and physical properties essentially similar to water is the radioactive isotope of hydrogen, ^3H , (tritium, T), available in the form of tritiated water, HTO. The preliminary laboratory experiments involve spherical rocks initially saturated with tritiated water. These rocks are suddenly immersed in a completely mixed tank of unlabeled water, and measurements of the concentration of the tritiated water in the external water are made as a function of time. A mathematical model has been designed to represent this physical system (see Ref. 1).

An important property of fractured rock in a geothermal reservoir is its thermal conductivity. The importance of artificial fracturing methods to stimulate the productivity of geothermal reservoirs will depend partly on the change in the thermal conductivity of the rock caused by fracturing. To our knowledge, there is no information on the effect of crack porosity on the thermal conductivity of rock samples. Thermal conductivity measurements will be made before and after stressing of rock samples. The pressure effects (vaporization of pore fluid and crack closure) will be examined by measuring the thermal conductivity of samples saturated at elevated temperature with varying confining pressures. The heat pipe effects will be examined by producing a temperature gradient along the core axis. The use of fluids to saturate the rock with different latent heats of vaporization should show the extent of an increase in heat conduction due to the heat pipe effect in cracked rock specimens (see Ref. 1).

B. Geothermal Reservoir Physical Models

Whiting and Ramey (Ref. 7) presented the application of energy and material balances to geothermal reservoirs. Although applied to a field case with success, later applications indicated a need for modification (see Refs. 8, 9, and 10). The need for actual data to test conceptual models has been apparent for some time (Ref. 11). Previous works concerned unconsolidated sand models, although a study by Strobel did include a consolidated sand. Strobel's study concerned cyclic production and reheating of a single consolidated sandstone geothermal reservoir model. This work will be repeated with both natural and synthetic sandstone cores with more complete instrumentation.

V. RADON IN GEOTHERMAL RESERVOIRS

The study of radon occurrence and transport in geothermal resources has been undertaken as an initial evaluation of the use of radon as a diagnostic tool for studying the performance of geothermal reservoirs. Another objective was the evaluation of environmental implications of radon release. This study includes three major tasks: (1) selection and implementation of a method for measuring radon, (2) evaluation of possible field sampling techniques, and (3) survey of actual radon occurrence in geothermal resource areas, both vapor- and liquid-dominated.

Radon emanation has been studied with respect to groundwater flow, natural gas production, and uranium prospecting (e.g., Refs. 12, 13, and 14). The extent of radon release to convective geofluids is dependent on several factors including the distribution of radium through the rock matrix and the surface area available for escape of recoiling radon atoms into the fluid. For homogeneous rock, the release of radon is related to particle size. In heterogeneous material other factors may obscure particle size dependence (see Ref. 1).

The question of radon as a possible environmental contaminant has been raised by Scott (Ref. 15), largely on the basis of data obtained in New Zealand resource areas. Large radon concentrations were observed in fumaroles and pools in the Rotorua-Taupo region. Therefore, our sampling program was conducted with a view to estimating the magnitude of any potential environmental problem. Some of the tasks already accomplished include: (1) development of a Radon Measuring System and construction and testing of the apparatus, (2) development of a field sampling technique, and (3) start of a field survey program with collection of samples from The Geysers steam field and from the Imperial Valley. Results are presented in Ref. 1. Field surveys are continuing.

VI. MATHEMATICAL MODEL

Advances have been made in the modeling of geothermal fluids production in three main directions. The first direction is a general view of the many complex thermal, fluid dynamic, and other physical processes. The second direction is the formulation of a mathematical description of a simplified system

to obtain a solution describing the behavior of this system. The third direction is matching the bench-scale experimental results to simulate the boiling flow of steam and water at elevated temperatures. Figure 6 presents the results of one simulation of a bench-scale geothermal reservoir model experiment. Figure 6a presents the computed pressure history, while Fig. 6b presents the computed liquid content of the system. Although not shown, the temperature history of the system was also computed (see Ref. 1, Fig. 48). Development of a more sophisticated model continues.

VII. CONCLUDING REMARKS

During 1974, the main components of most projects in the Standard Geothermal Program were completed and initial runs performed successfully. Augmentation of system instrumentation, completion of improvements in design, and collection of experimental data are in progress. All projects are developing satisfactorily.

NOMENCLATURE

- h = heat transfer coefficient (Btu/hr-ft²-°F)
- L = characteristic length of body (ft)
- k = thermal conductivity (Btu/hr-ft-°F)
- $H_1 A_1$ = heat transfer conductance from water/rock to metal (Btu/hr-°F)
- $H_2 A_2$ = heat transfer conductance from metal to surroundings (Btu/hr-°F)
- $M_1 C_1$ = heat capacitance of metal in chimney (Btu/°F)
- $M_2 C_2$ = heat capacitance of metal in chimney (Btu/°F)
- S = energy source (electric heater) (Btu/hr)

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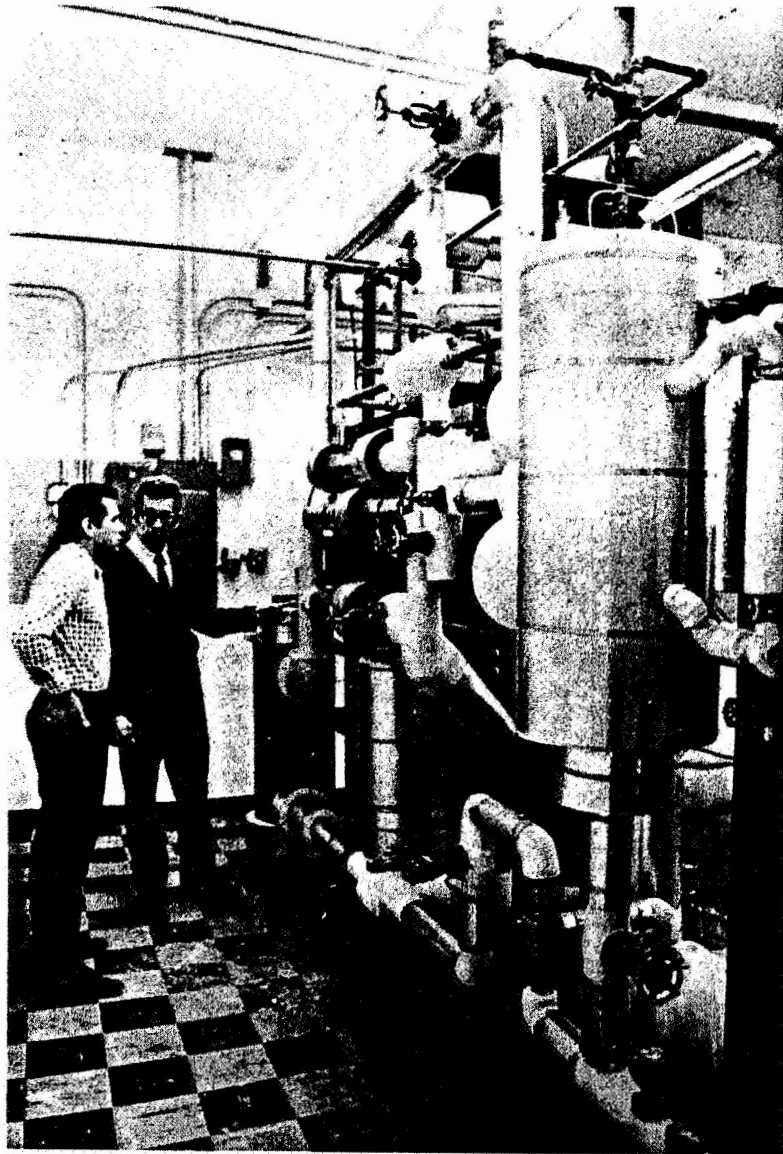


Fig. 1. Photograph of chimney model system showing operating controls

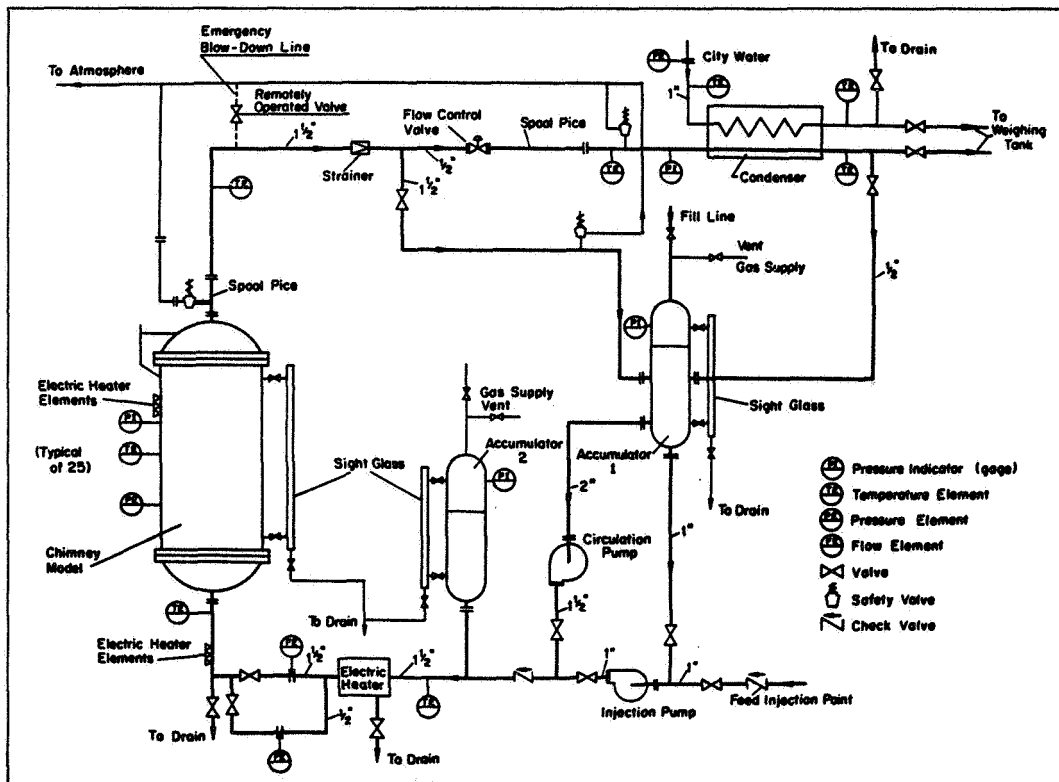


Fig. 2. Piping and instrumentation diagram of the chimney model system

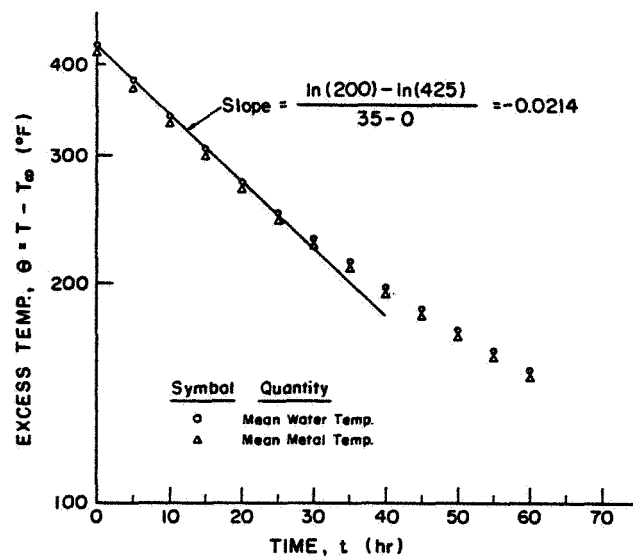


Fig. 3. Experimental cooldown transient for chimney model loaded with water only

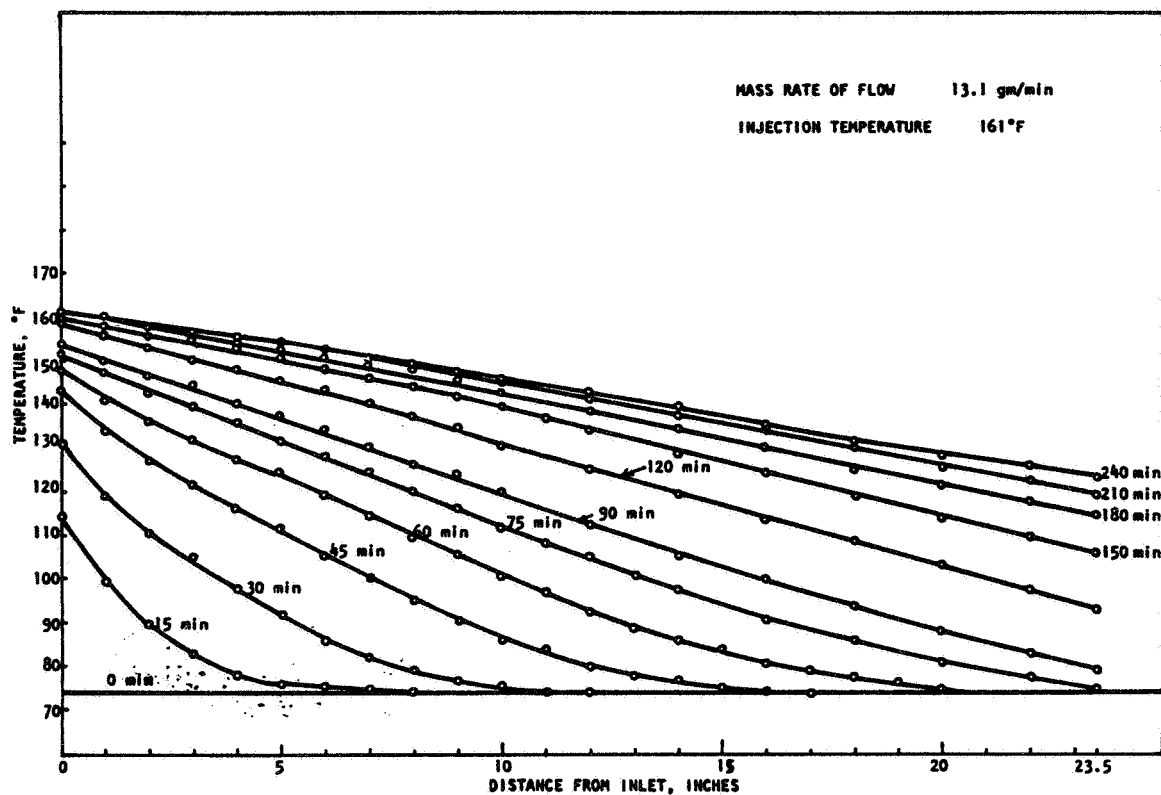
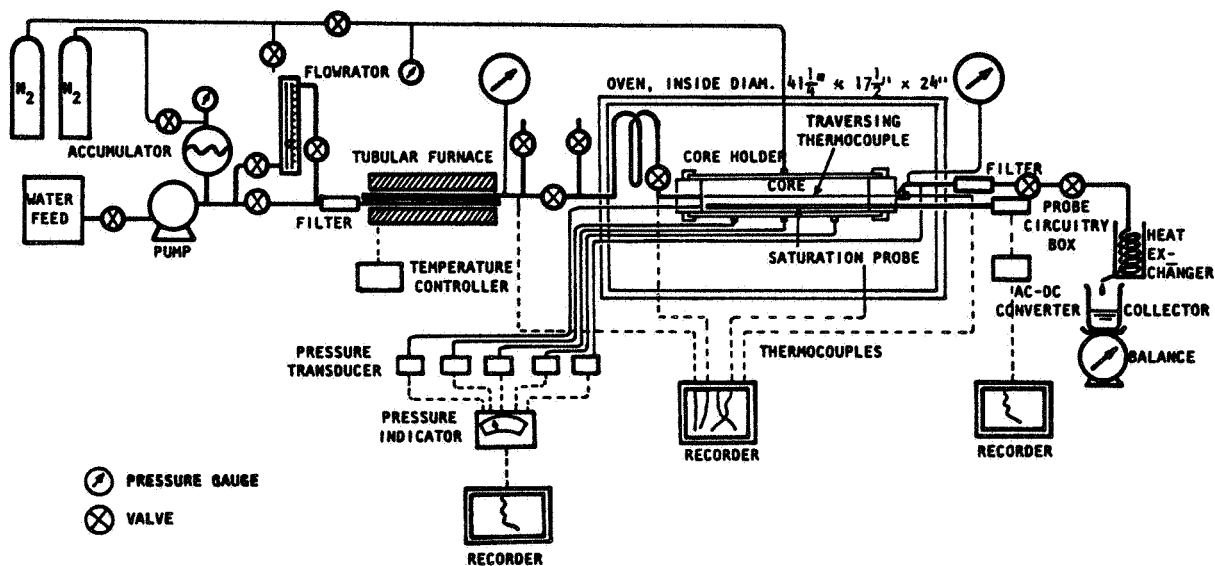


Fig. 5. Temperature vs distance for hot water injection

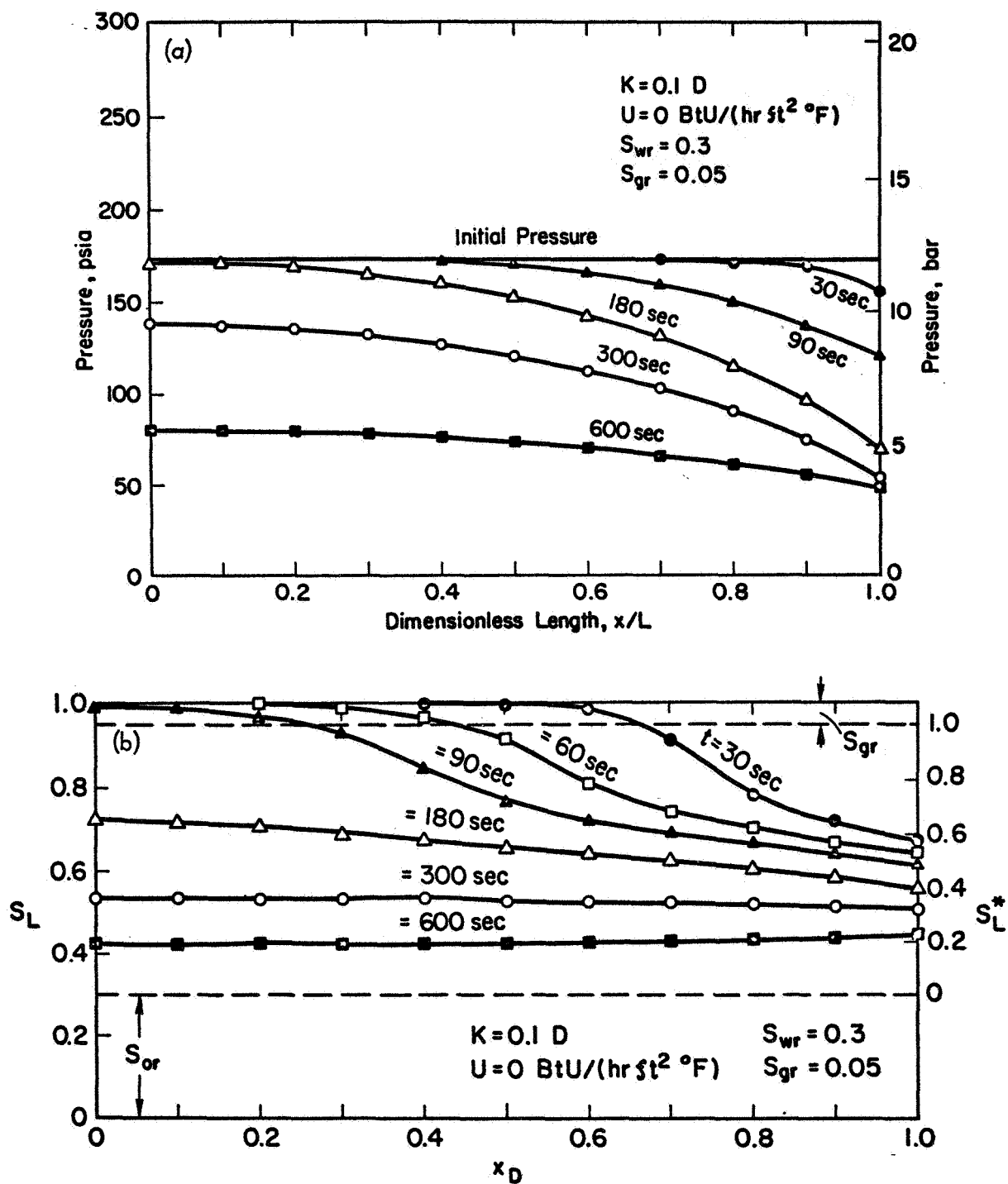


Fig. 6. (a) Simulation No. 1 of pressure history, (b) simulation No. 1 of saturation history

GEOTHERMAL DOWN-WELL PUMPING SYSTEM

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A key technical problem in the exploitation of hot water geothermal energy resources is down-well pumping to inhibit mineral precipitation, improve thermal efficiency, and enhance flow. A novel approach to this problem involves the use of a small fraction of the thermal energy of the well water to boil and super-heat a clean feedwater flow in a down-hole exchanger adjacent to the pump. This steam powers a high-speed turbine-driven pump. The exhaust steam is brought to the surface through an exhaust pipe, condensed, and recirculated. A small fraction of the high-pressure clean feedwater is diverted to lubricate the turbine pump bearings and prevent leakage of brine into the turbine-pump unit. A project demonstrating the feasibility of this approach by means of both laboratory and down-well tests has just started under an NSF grant. The status and plan of this project are presented.

I. INTRODUCTION

The Sperry Research Center has been engaged for two years in the analysis and design of a novel type of pumping system for geothermal liquid-dominated wells. Since July 1974 we have been under a grant from the National Science Foundation through its Research Applied to National Needs (RANN) program to build and test this system. Field testing in a geothermal well is expected to begin in July 1975, possibly in the Imperial Valley of California.

II. WELL DYNAMICS

Figure 1 illustrates in a simplified geologic situation what is known as a hydrostatic well. The water table in the strata surrounding the well is essentially at the surface of the ground and the water increases in temperature as we go deeper in the earth. With the valve closed to prevent flow, the water inside the well casing will assume virtually the same thermal gradient as the water outside and, therefore, being of the same average density, will rise in the casing essentially to the level of the outside water table.

If the valve in our illustration is opened (Fig. 2) and the well caused to start flowing by some means, the hot water flowing up the casing will progressively lower the average density of the water column and the flow velocity will increase accordingly.

When 212°F water approaches the surface, a portion of it will flash into steam, lowering the column density even more and again accelerating flow. The level at which this flashing begins will move down the well as increasingly hot water comes to the surface and will stabilize at a level as determined by:

- (1) The bottom hole temperature (temperature losses up to the flash level in a flowing well are negligible).
- (2) The average density of the mixed liquid and vapor column above the flash point.
- (3) The two phase flow losses from the flash level to the surface.

The mixture of steam and water will arrive at the surface at a temperature of 212°F and (in a 400°F well, for example) as approximately 20% saturated steam.

The quantity of flow from the well will depend on the very complex interrelation between the thermal and saline gradients in the water outside the well, flow losses in the strata feeding the well and in the well casing, and the actual density gradient in the column above the beginning of flashing. When this natural flowing method is used to produce a well, as it is in a few places in the world for generating electricity, an additional impedance is inserted in series at the surface (equivalent to closing down our valve somewhat) so that a pressure drop is introduced between atmosphere and the Rankine cycle conversion equipment. Thus, the water steam mixture will enter the energy conversion process at a higher temperature than 212°F (in a 400°F well, say, at 325°F, 97-psia pressure, and 10% steam).

There are several drawbacks to such a naturally produced well; among them are:

- (1) Well flow is reduced to below that of open wellhead flow by the added impedance.
- (2) Geothermal waters are usually considerably contaminated with dissolved solids. The process of flashing causes the most troublesome of these compounds to precipitate, which then coat the well casing (sometimes seal it) and, more seriously, foul surface equipment, such as heat exchangers.
- (3) The lowered temperature caused by the flashing reduces the efficiency of the surface conversion equipment.

III. WELL PUMPING

If a pump is introduced into the well below the flash point and sufficient pressure is added to the water so that it will not flash even on the surface, the above problems are largely negated:

- (1) Flow can be increased, even above the well's natural flow rate, with a consequent increase in available energy.

- (2) Water is brought to the surface at or near bottom hole temperature with a consequent increase in surface conversion efficiency.
- (3) If the water remains under pressure, the dissolved carbon dioxide remains in solution and prevents the most troublesome constituents (mainly carbonates) from precipitating. Thus, except for silica, which will precipitate when the water is cooled, the most serious problems are eliminated. The effect of silica remains to be determined, but experiments to date are somewhat encouraging.

IV. PUMP WORK

The following factors determine the amount of work to be done by the pump:

- (1) Requirements. The water must arrive at the surface somewhat above the saturation pressure. In a 400°F well, this is approximately 247 psia, and with a 10% pad, 272 psia. If there is a pump on the surface circulating the hot well water, then the net positive suction head (NPSH) requirement of this pump must be added to the pressure.
- (2) Thermal Lift. As mentioned before, the column of water inside the well, when flowing, will be essentially at bottom hole temperature, while the water in the strata outside will have some thermal gradient from the low surface temperature to the high temperature at well bottom. This effect, of course, reduces the amount of pump work and can be of considerable magnitude. A 400°F hydrostatic well of relatively pure water, 5000 feet deep and with a linear temperature gradient in the surrounding strata, will gain approximately 150-psi pressure due to its thermal lift.
- (3) Well Productivity. Bottom hole pressure will, of course, drop as flow is increased because of friction in the surrounding strata, a property described in the oil industry by the term "productivity index." The pump must make up this pressure loss, and the practical matter of energy expenditure would seem to limit consideration to wells where this pressure loss is no more than a few hundred psia at acceptable flow rates.
- (4) Casing Flow Loss. The flow in the casing will always be turbulent, and pressure loss will be proportional to flow squared. A 1000-gpm flow in a 8-5/8-in. casing will generate a loss of perhaps 50 to 100 psi in a 5000-foot-deep well, depending on pipe roughness. A practical casing design for such flows might be 8-5/8 in. up to just below the pump and 10-3/8 in. or 13-3/8 in. above.

V. CONVENTIONAL PUMPING SYSTEM

Figure 3 shows the elements of a conventional pumping system. If the well is pumped only at the naturally flowing rate, then the pump must be placed in the well a sufficient depth below the natural flash level to provide sufficient NPSH for the pump, which is the required pressure above saturation pressure of the fluid at its particular temperature to prevent the pump from cavitating. If a greater quantity than the natural rate is pumped, then the pump must be at an additional depth as determined by the added flow losses in the strata and in the well casing below the pump. It appears that this depth could well be 1000 feet or more for optimized well production in the general case.

The pump will be driven by energy sent down from the surface in some sort of conduit, an electric cable or a hydraulic tube, for example. This energy will, in fact or in effect, be obtained from the well water itself and before ending downhole as pressure added to the well flow be transformed a number of times, with each transformation resulting in a loss of efficiency. For example, this can be shown for the hydraulic system:

- (1) Heat to turbine torque.
- (2) Torque through alternator to electricity.
- (3) Electricity through motor to torque.
- (4) Torque through pump to hydraulic power.
- (5) Hydraulic power downhole through hydraulic motor to torque.
- (6) Torque through pump to pressure and flow in well water.

VI. THE SPERRY PUMPING SYSTEM

In order to avoid this multiple-energy conversion problem with its attendant loss in efficiency, the Sperry Research Center is constructing a system which will not bring energy down from the surface to operate the pump, but will instead extract energy from the hot well water downhole at the site of the pump. It will have only two energy conversions--heat to torque and torque to pressure--rather than several. The principle involved is shown in Fig. 4. A small quantity of clean water (perhaps 1 or 2% of well water flow) is sent downhole to a heat exchanger (several lengths of standard oil field casing), dropped in pressure by a ΔP valve, and then vaporized and superheated by the well water flowing upward around the outside of the heat exchanger piping. This superheated steam is used to drive a turbine and a mixed flow pump impeller at a speed of from 15,000 to 30,000 rpm. The turbine exhaust is returned to the surface through another concentric pipe, where it is condensed and returned downhole. Thus, the turbine working fluid is contained in a closed loop, and well water is excluded from this system. Figure 4 also shows how some of the clean water continues down the central pipe past the entrance to the heat exchanger and is used to lubricate

the turbine and pump bearings. Since this clean water is at a higher pressure than the well water, the contaminated well water is prevented from entering the turbine.

The boiler manifold contains a threshold valve, which prevents water from entering the boiler unless feedwater pressure is above well water pressure, and the ΔP valve (mentioned above), which drops feedwater pressure to permit boiling and also to permit changing boiler pressure by varying feedwater pressure at the surface. Since mass flow to the turbine is a function of boiler pressure, we can effectively control turbine output from the surface.

An additional energy saving accrues from this system, since the energy for pumping ultimately comes from the well water anyway. It is better to remove this energy downhole. The temperature is thus lowered somewhat and arrives at the surface with a correspondingly lower saturation pressure, requiring less pressure added. In a 400°F well, this typically could amount to an additional 20% energy saving. At first glance, this process would seem to place an undue penalty on the efficiency of the surface conversion system as demonstrated by the Carnot principle. Nevertheless, it is easy to show that any pump, however it operates, will remove just its required portion of the available energy from the water. It does not matter whether it takes this energy from the top of the cycle (as we do), from the bottom of the cycle, or from an infinite number of points in the cycle (as in the case of a pump which takes its energy electrically from the main conversion system).

A simplified schematic of the turbine-pump unit for our first test is shown in Fig. 5. It is designed to fit in an 8-5/8-in. casing, although for the field test it will be adapted into a larger casing.

The bearings are hydrodynamic and are of tilting pad design. The thrust bearing has operated on hot water in the lab at three times our design load. The ball bearing operates only during start-up, when the high-pressure well water causes an upward thrust on the shaft until pump thrust builds up and thrusts the shaft downward through a 0.015-in. end play.

The turbine is a two-stage pressure, compounded single-wheel design with its exhaust being redirected upward through its spoked hub.

In the expected test situation, the pump and test parameters will be approximately as follows:

Well temperature	400°F
Turbine output, nominal	155 HP
Turbine output, max	220 HP
Pump output	1000 gpm at 200 psi ΔP
Depth in well	850 ft

NPSH	100 psi
Well water ΔT , nominal	15 to 20°F
rpm	17,000
Specific speed	5,400
Suction specific speed	8,000

This first unit has been designed with the objective of a successful test rather than efficient performance or maximum output. The system may remove from the well water as much as 10°F per 100 psia added. (Note that this parameter is independent of the quantity pumped.) With an optimized system and some amount of development, however, we feel that this will drop to 5°F/100 psi added, which is an amount considerably below that of any other approach we are aware of. Efficiency in pumping geothermal fluids is, of course, of prime importance since they have such a small amount of available energy to begin with. It is also evident that if a well has an inherently poor productivity index, a pump or any other expedient will not turn it into a worthwhile asset.

VII. PROGRAM

Lab tests of the impeller will start by December 1, 1974, and tests of the complete turbine-pump in February, 1975. Field testing is scheduled to begin in July, 1975, probably in the Imperial Valley, and we hope to complete two months' total operation during a four-month period.

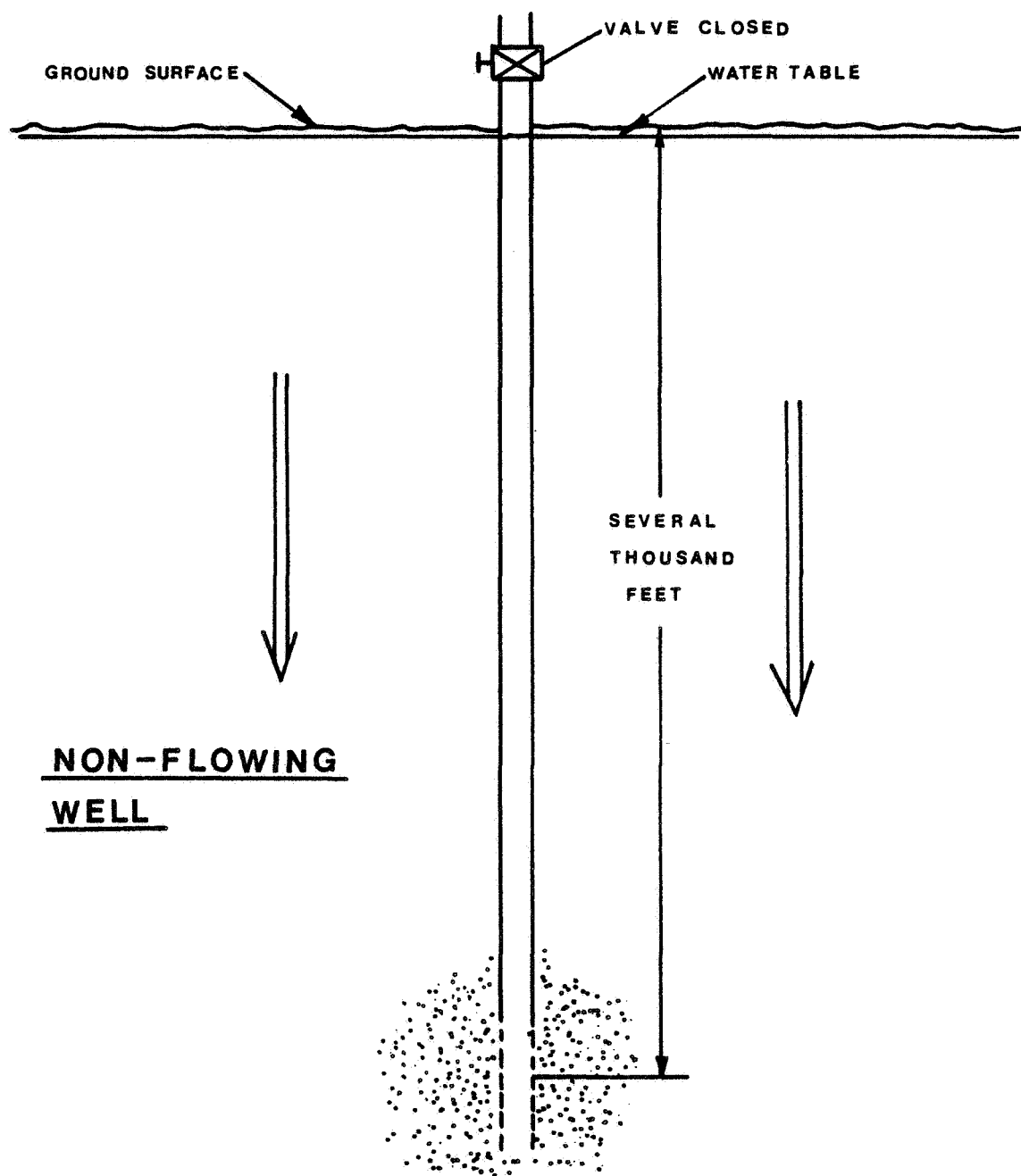


Fig. 1. Schematic of hydrostatic geothermal well

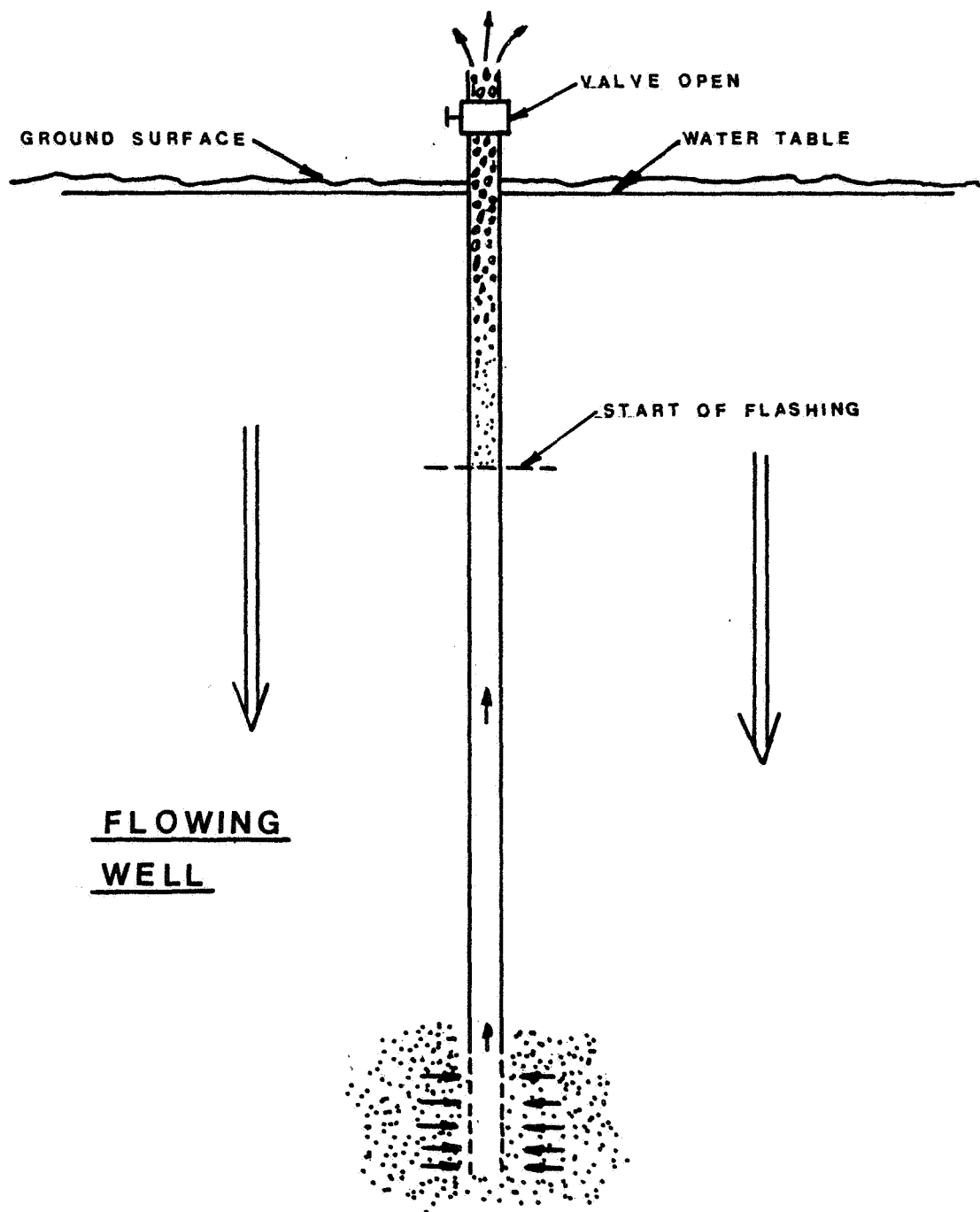


Fig. 2. Well of Fig. 1 with low flow rate

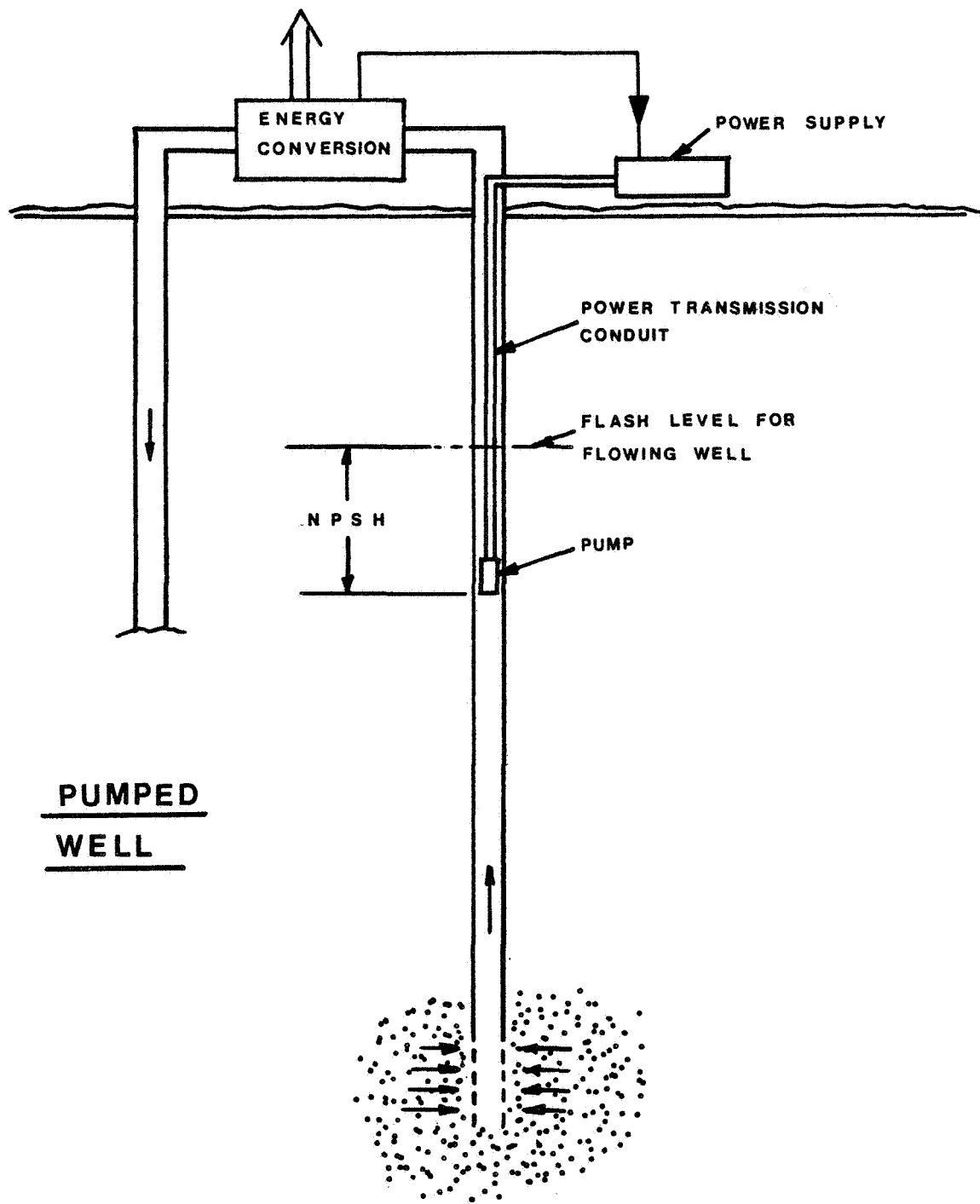


Fig. 3. Schematic of conventional well pumping system

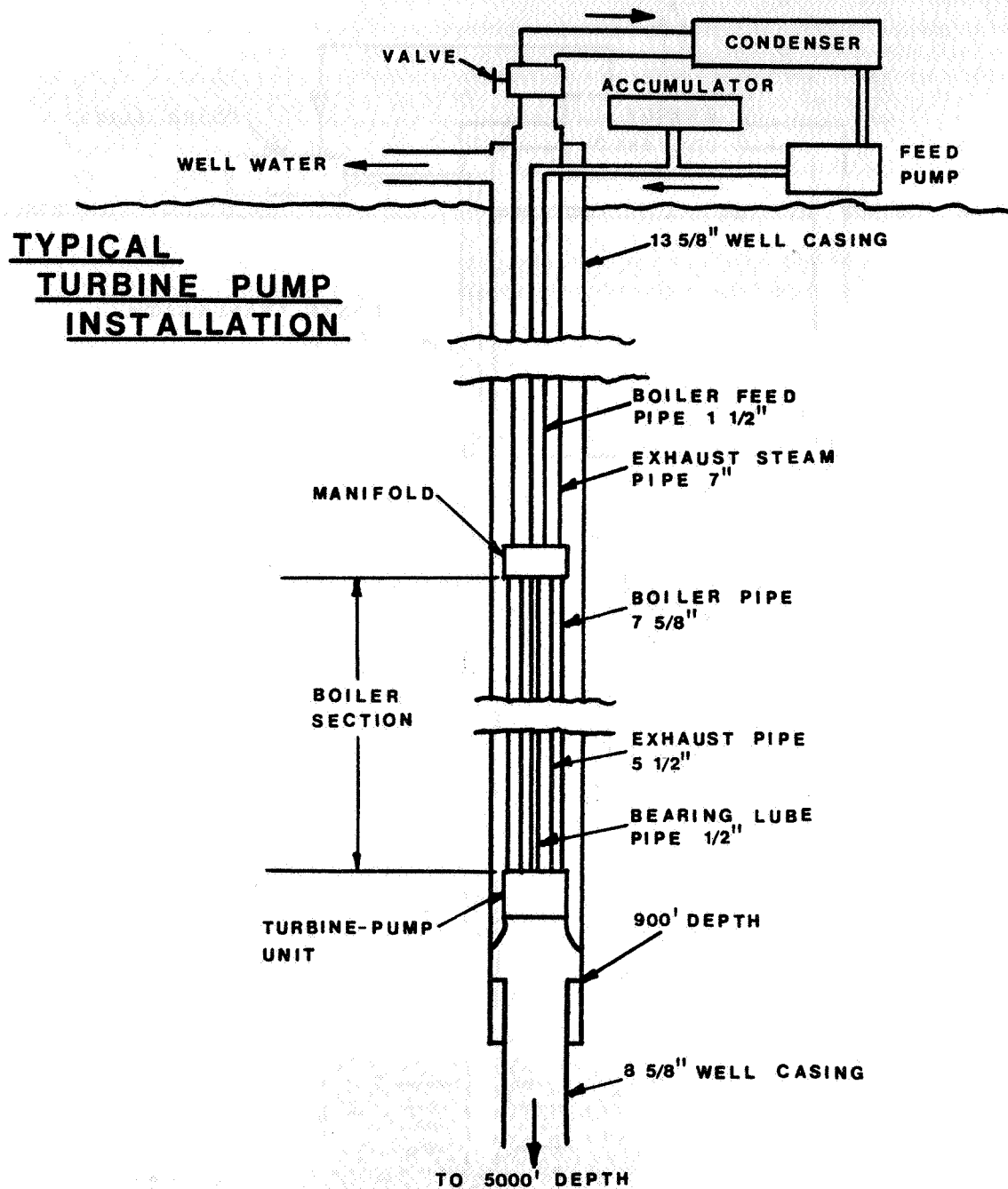


Fig. 4. Schematic of Matthews pumping system for geothermal wells

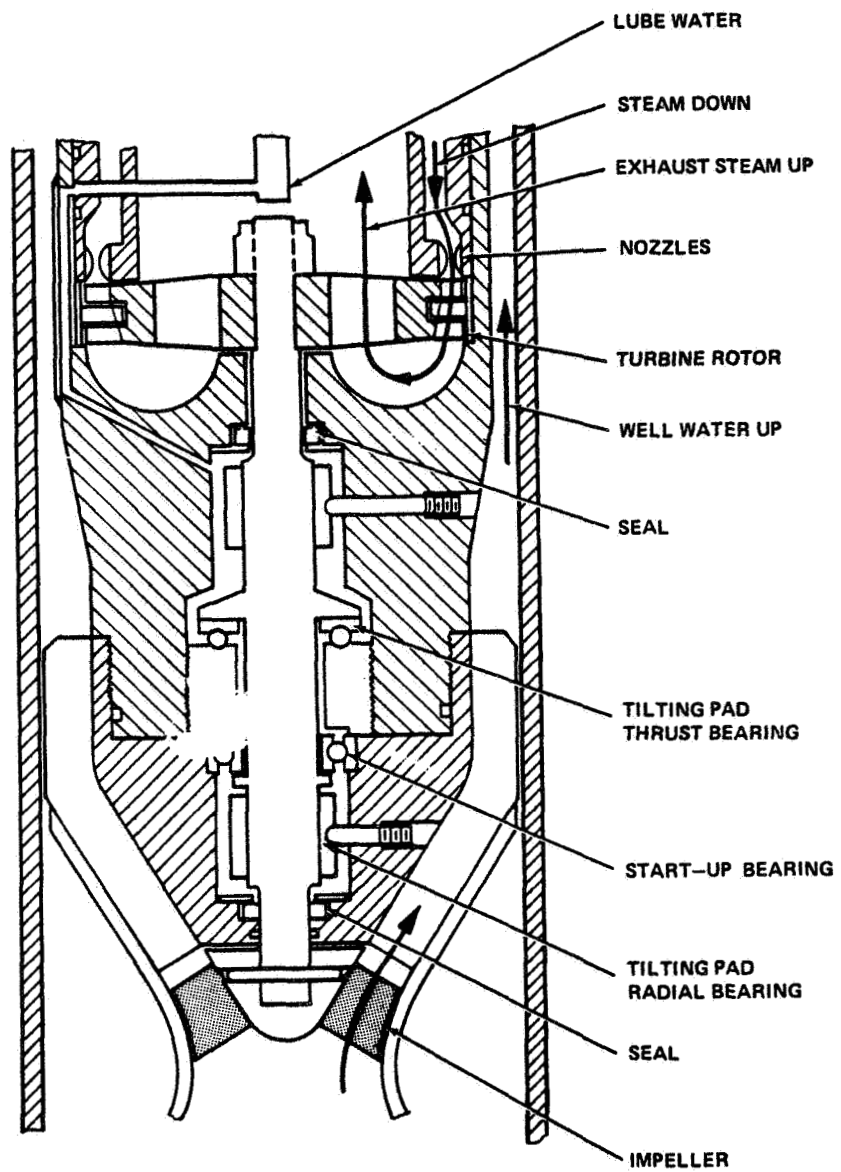


Fig. 5. Schematic of turbine-pump unit for Matthews pumping system

INVESTMENT AND OPERATING COSTS OF BINARY
CYCLE GEOTHERMAL POWER PLANTS

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The purpose of this paper is to present typical investment and operating costs for geothermal power plants employing binary cycle technology and utilizing the heat energy in liquid-dominated reservoirs. These costs are developed as a function of reservoir temperature. The factors involved in optimizing plant design are discussed. A relationship between the value of electrical energy and the value of the heat energy in the reservoir is suggested.

I. INTRODUCTION

Interest in the production of electric power from geothermal resources is increasing exponentially. Much of this interest, both private and public, is focused on the exploitation of liquid-dominated reservoirs for the simple reason that there is only one exploitable vapor-dominated reservoir (the Geysers) in the United States, while the rest are liquid-dominated. These latter reservoirs are simply superheated bodies of hot water lying deep below the surface and containing varying quantities of salts, minerals, and noncondensable gases.

It appears that binary cycle plants will be used extensively to produce power from hot water reservoirs. The problems inhibiting rapid development of such reservoirs appear to be solved or well on the way to solution.

Our firm has been participating in the development of three hot-water reservoirs in California. These are Mammoth (Long Valley), Niland (Imperial Valley) and Heber (Imperial Valley). Any one of them could be the first in the United States to be a source of electric power from a hot-water reservoir.

The status of these projects will be discussed briefly, but the main purpose of this paper is to present capital and operating cost figures for binary cycle power plants based upon the ABC process developed by members of our firm, to discuss the factors involved in optimizing a plant design, and to suggest a relationship between the value of electrical energy produced and the value of the heat energy in the hot water.

II. THE BINARY CYCLE

The binary cycle has been described in two earlier papers (Refs. 1 and 2) presented by members of our firm, and has been described by others as well (Ref. 3). The industry seems to have firmly adopted the term "binary cycle", although the term "organic Rankine cycle" is more explicit, since it is exactly what it is. Figure 1 is a flow diagram of a typical binary cycle. The working fluid is heated and vaporized by exchange with the hot water, expanded in a turbine, condensed to a liquid with a cooling medium and pumped to the exchanger, thereby completing the cycle.

One variation of the binary cycle is the patented Magmamax process owned by Magma Energy, Inc. Another is the ABC process developed by members of my firm. In the latter case patents have been applied for but not yet granted. The ABC process patent applications include methods of scale control and prevention as well as innovative concepts in the binary cycle itself. To the best of our knowledge none of our claims conflict with the Magmamax patent.

III. SCALING

The major problem inhibiting the construction of binary cycle plants has to do with the prevention or control of scaling in the tubular exchangers transferring heat between the hot water and the working fluid. In order to gain insight into this problem, Magma Energy, Inc. at Mammoth and San Diego Gas & Electric Company (SDG&E) at Heber are operating heat exchange test units which we designed and fabricated. These units closely simulate the conditions expected in commercial size heat exchangers. Both units have been operating in recent weeks. Some reduction in heat transfer rates has occurred in both units, but it is too early to evaluate the magnitude of the problem or to decide what to do about it. We believe that an economical solution will not be difficult to find.

The solution to the scaling problem at Niland is to heat the working fluid with flashed steam rather than hot water. It is necessary to remove the entrained solids from the steam and this has been done successfully employing a proprietary scrubber patented by our Mr. Hutchinson.

Direct contact heat exchange between the hot water and the working fluid has been suggested as a means of eliminating scale deposition. Members of our firm have two patent applications covering two direct contact concepts. Claims for both applications have been allowed. We are seeking NSF support to develop our Mr. Sheinbaum's concept which is similar to the concept proposed by R. F. Boehm, et al., in a recent paper (Ref. 4). SDG&E have the hardware on hand for demonstrating the concept invented by our Mr. Hutchinson and plan to operate a pilot plant in connection with the operation of their geothermal test facility at Niland.

Earlier this year we completed a conceptual design and cost estimate for Magma Energy's proposed installation at Mammoth. It is our understanding that authorization for construction is awaiting completion of their field testing

program. More recently we received an assignment from SDG&E to redesign their Niland geothermal test facility based on using flashed steam and our proprietary scrubber. Both installations will employ binary cycle technology.

IV. ECONOMICS

As one would anticipate, the economic viability of a geothermal development is clearly related to the reservoir temperature, higher temperatures resulting in lower capital costs and decreased hot water consumption.

A. Capital Cost

The relationship between reservoir temperature and capital cost is illustrated graphically in the upper curve of Figure 2 for a 50 MW installation. At 250°F the capital cost is about \$475/kW, declining to \$250/kW at a 500°F reservoir temperature. These capital costs are representative of costs prevailing during the second quarter of 1974. They represent the installed cost of a battery limits plant. They do not include land cost, working capital, royalties, nor costs associated with the production, transmission to the plant, and reinjection of the hot water. The assumption is made that the hot water is nonfouling, that steel may be used in the hot water exchangers, and that H₂S is present in negligible amounts. A further assumption is made that reservoirs are pumped at temperatures up to 400°F and are self-flowing at temperatures above 400°F, producing at the surface a mixture of steam and hot water. At 500°F, the well-head mixture of steam and hot water is at a pressure of 200 psig and a temperature of 390°F.

These cost figures should be used with caution and the basis of the estimates should be kept clearly in mind, because local conditions can have a major effect on capital cost.

There is a significant economy of scale in comparing the installed cost of a 10-MW unit and a 50-MW unit. A 10-MW unit will cost 25% to 35% more per kilowatt than a 50-MW unit.

B. Optimization

In concept the binary cycle is simplicity itself. It is a relatively simple matter to design a plant that will work, but not so simple to provide an optimum design, that is one which will give maximum return on invested capital.

In the typical case, a public utility will own and operate the power plant and will buy heat energy from the developer of the field. In order to design an optimum plant the utility must furnish the engineer the value of the electricity to be produced and the utility's method of economic analysis. The developer must furnish composition, pressure, temperature, and flow rates of the available hot water. With the foregoing data in hand the engineer can produce an optimum design and can estimate realistic capital investment and operating costs.

In the process of optimization the engineer must make many decisions including:

- (1) Selection of a working fluid. The optimum fluid varies with the temperature of the reservoir. Propane (boiling point = -44°F) might be used in a low-temperature reservoir, while hexane (B.P. = $+156^{\circ}\text{F}$) might be the best fluid in a high-temperature reservoir.
- (2) Selection of turbine inlet pressure and temperature. Optimum turbine inlet pressures will range from 400 psig to 800 psig, and inlet temperatures may be 20°F to 40°F lower than the incoming hot water.
- (3) Selection of condensing temperature. This will vary with the method of cooling as well as local climatic conditions. The lower the condensing temperature the higher the efficiency of the plant. In cold climates air cooling may be the best selection. In other areas, a cooling tower is usually best, and local weather conditions will dictate the optimum cooling water temperature and condenser temperature. Condensing temperatures may vary from 50°F in very cold climates to 120°F in very hot climates.
- (4) Selection of turbine. It is most important to select a hydrocarbon turbine having the highest possible efficiency. At the present state of development, the radial inflow type appears to be the front runner. The established manufacturers quote thermodynamic efficiencies in the range of 85%. The reason that high efficiency is important is that the capital cost and operating cost of a power plant are inversely proportional to turbine efficiency. For example, a plant with a 75% efficient turbine will cost just about $85/75 = 1.13$ times a plant with an 85% efficient turbine.
- (5) Selection of heat exchangers and condensers. Large fixed-tube-sheet tubular exchangers built in accordance with the Standards of The Tubular Exchanger Manufacturers Association are recommended. Careful attention to design is necessary because heat exchangers are the single most expensive item in the plant. Single units are available having diameters up to six feet, lengths up to 80 feet and weighing up to 300 tons. Such designs have been developed and proven over a period of years by the hydrocarbon processing industry. Optimum temperature approaches must be determined in exchangers, condensers and cooling towers.

We have developed a computer program which we use in our optimization studies. The program makes it possible to determine the effect on net power output easily and quickly by making changes in the previously outlined variables.

We would like to emphasize that the major equipment is all "state-of-the-art" and "off-the-shelf" equipment. The exchangers, pumps, turbine, generator, cooling tower, and pressure vessels may be purchased from established

vendors on a guaranteed performance basis. The physical and thermodynamic properties of the working fluids may be estimated with precision. Thus the technical risk in constructing a power plant of this type is minimal, except for the uncertainty in the design of the hot water/working fluid heat exchanger.

A binary cycle plant bears more resemblance to a chemical process or a natural gas processing installation than it does to a conventional fossil-fueled power plant.

This is not to say that there will not be new hardware, techniques, and processes developed in the future which will improve performance and economics.

C. Performance of the ABC Process

The performance of the ABC process is shown in the lower curve of Figure 2. Hot water consumption in pounds per net kWh is plotted against reservoir temperature. The reservoir fluid is assumed to be water, and the cooling water temperature is assumed to be 65°F. A net kWh is the salable power and takes into account the power required to operate the cooling system and the working fluid pumps, together with realistic estimates of the mechanical and electrical efficiency of the components of the finished plant.

Each point on the curve represents the results of a number of optimization studies made with respect to choice of working fluid, turbine operating conditions, and heat exchanger temperature approaches. The quality of hot water required varies from about 400 lb/kWh at 250°F to about 55 lb/kWh at 500°F. For practical purposes, this curve is independent of capacity.

D. Operating Costs

The cost of operating a geothermal power plant is the sum of fixed charges and other direct operating costs. We have taken annual fixed charges to be 22% of the capital cost of the plant. This figure includes the following:

- (1) Capital return and interest.
- (2) Income taxes.
- (3) Property taxes.
- (4) Depreciation.
- (5) Insurance.
- (6) General and administrative expense.
- (7) Maintenance labor and materials.

Since the cost of maintenance is a capital related item, this cost has been included in the fixed charges.

We estimate that other direct operating costs will be about 1.4 mills/kWh. Such costs include operating labor, supervision, chemicals and supplies and plant overhead. This cost can vary quite a lot depending on local conditions.

On the basis that the plant operates 8,000 hr/yr, the relationship among the value of the hot water, the reservoir temperature and the value of the electricity is presented in Figure 3. These variables are related by the following equation:

$$P = F + O + W$$

where

P = value of electricity produced in mills/kWh

F = fixed charges in mills/kWh

O = direct operating costs in mills/kWh

W = value of hot water produced in mills/kWh

At 20 mills, the value of 500°F water is about 12 mills/kWh declining to about 5.5 mills/kWh at 250°F. The value of Btu's extracted from the hot water may also be estimated. For example with 20 mill power, the heat extracted is estimated to be about 36¢/MM Btu at 350°F and about 51¢/MM Btu at 500°F. The corresponding numbers for 30 mil power are 75¢/MM Btu and 94¢/MM Btu.

A recent paper by R. A. Walter, et al., entitled "Evaluation of Small Power Systems for use with Geothermal Reservoirs" (Ref. 5) studies the effect of capacity and reservoir temperature on capital costs and operating costs for both binary and steam flash cycles. We note significant differences between their estimates and ours.

We believe these differences stem largely from the fact that our curves are based upon optimized cycles, whereas their curves are based upon employing a single fluid over the whole range of temperatures considered.

The data presented herein indicate what a utility might afford to pay for energy under various assumed conditions. No consideration is given to whether such payment would provide the developer with an adequate return on his investment.

This presentation is intended to provide useful economic guidelines to government, utilities, developers, and others. Each group can apply its own method of economic analysis to prepare similar estimates.

We may have raised more questions that we have answered, including:

- (1) On what basis should a developer sell and a utility buy the energy in a hot water reservoir?
- (2) Under what conditions do the economics favor a steam flash cycle or a hybrid cycle rather than a binary cycle?
- (3) How do the economics compare with other new sources of electric power?
- (4) Should optimization studies include the costs associated with the production and reinjection of the water and, if so, how do you go about it?

We would welcome your response to these questions.

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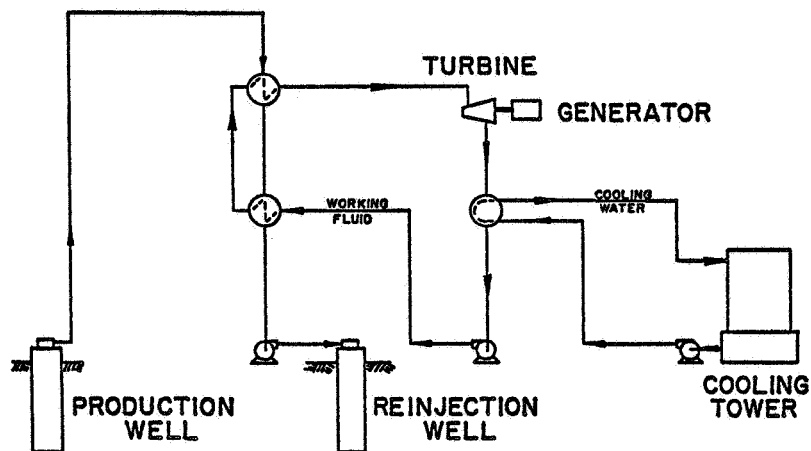


Fig. 1. Typical binary cycle

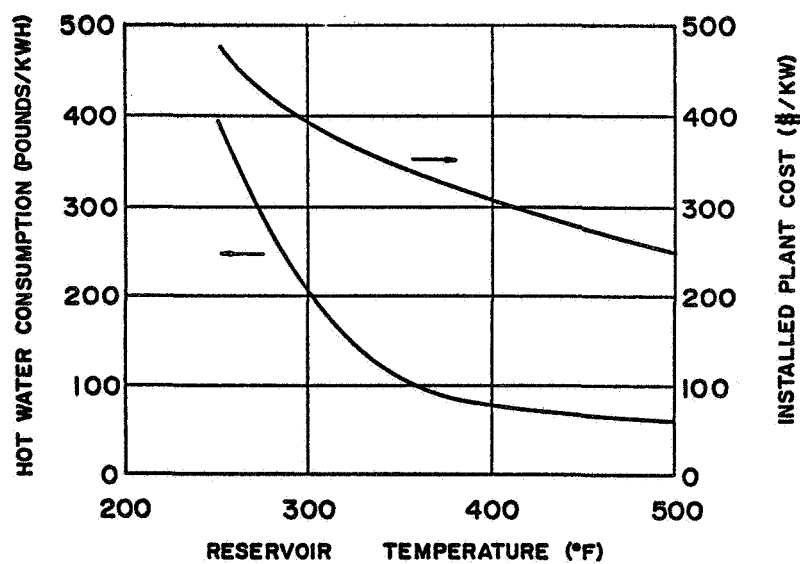


Fig. 2. Effect of reservoir temperature on water consumption and installed plant cost (basis: 50-MW plant)

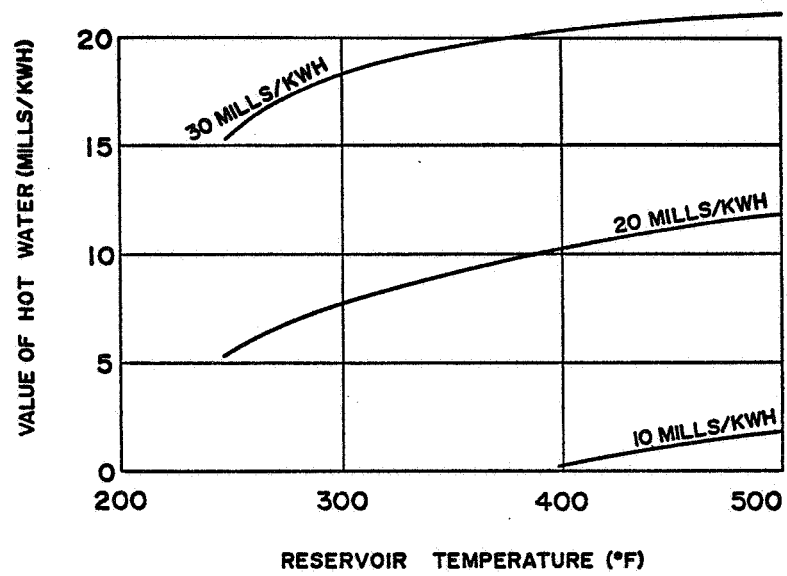


Fig. 3. Effect of reservoir temperature on value of hot water at varying values of power

HELICAL ROTARY SCREW EXPANDER POWER SYSTEM

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A technical survey made by the Jet Propulsion Laboratory (JPL) led to the conclusion that an energy converter well suited to wet steam geothermal fields could be a major stimulant to the development of these energy resources. The helical rotary screw expander, developed by the Hydrothermal Power Co., Ltd. (HPC), is a very promising candidate to fill this need. JPL has proposed to evaluate and characterize the screw expander in conjunction with HPC. The work will use commercial-size equipment operating on low saline and then hypersaline brine with members of the geothermal industry participating. The helical screw expander is a positive displacement machine of the Lysholm type which can accept the untreated corrosive mineralized hot water of any quality from a geothermal well. The subjects of corrosion, mineral deposition, the expansion process, the experience to date with a prototype and the proposed evaluation project are discussed.

I. INTRODUCTION

In all the world, there are only 12 locations where electrical power is presently generated from geothermal energy, providing a total installed capacity of about 1100 MW (Refs. 1-4). * In these locations energy is available from the ground as geothermal fluid, either in the form of steam (vapor-dominated fields) or in the form of hot brine (liquid-dominated fields). In all cases, energy is converted to electrical power by means of a vapor turbine as the prime mover. In the vapor-dominated fields (four locations), the procedure is essentially simple. Dry steam from the producing wells is

*For comparison: As of 1970, the world's largest high-pressure steam-driven turbogenerator was the 1150-MW unit at the TVA power plant at Paradise, Ky. Two nuclear plant additions now under construction at San Onofre, California will be 1140 MW each.

cleaned of entrained solids, and then passed directly to turbines which drive electrical generators. In the case of the liquid-dominated fields, the brine is either flashed to liberate steam, which is then separated from the residual brine and sent to the turbogenerators (seven locations), or it is used to boil a secondary fluid (one location) which in turn is sent to turbogenerators.

At present, the four vapor-dominated fields noted above have a combined, installed electrical capacity of 806 MW or 73% of the worldwide geothermal total. The largest of these is at The Geysers in California, where Pacific Gas and Electric Co. (PG&E) is systematically adding 100 MW capacity per year on a schedule that extends through 1980. These additions represent 10% of the annual increases planned by PG&E from all sources (Ref. 3). There are no reported technical problems sufficient to hamper this schedule. The schedule is planned to allow the orderly development and exploitation of the geothermal reserve, and is possible because the steam turbine is an ideal match for vapor-dominated fields. Technological problems which are encountered there, such as turbine blade erosion and corrosion, are handled in the normal course of doing business.

Unfortunately, vapor-dominated geothermal fields are scarce. This helps to explain why The Geysers is the only such geothermal power plant location in the Western Hemisphere. Far more prevalent, by an estimated ratio of 20 to 1, are the liquid-dominated fields which produce hot water or brine. It thus follows that, all other things being equal, if there are four steam fields producing electricity, there should be 80 wet fields similarly in production instead of the mere 8 mentioned above. But all other things are not equal. The ideal match of a prime mover compatible with a liquid well effluent has been historically absent, and so the exploitation of the wet fields has been seriously hampered. It has been necessary to produce a vapor to drive a turbine, either by flashing part of the brine to steam, or by boiling a secondary fluid in a heat exchanger. In the steam-flashing process, much energy is lost in the waste hot brine which flows from the steam separators, and the throttling step itself is inherently inefficient. Similarly, in the process involving a secondary fluid, substantial energy losses are associated with the temperature difference necessary to drive the heat exchanger and with the power demands for pumping the secondary fluid. (It may be noted that the world's pioneer geothermal power plant at the vapor-dominated field in Larderello, Italy, switched from the use of heat exchangers to the direct expansion of the geothermal fluid because of these inefficiencies (Ref. 1).)

In addition, supplementary process equipment, especially heat exchangers, is expensive. Moreover, and perhaps most serious, scale formation from the brine can be severe. It must be recognized that the hot brine has been in contact with minerals for a long time and will be in near equilibrium at reservoir temperatures. Therefore, as the brine is cooled, part of the dissolved solids will precipitate, especially on cool surfaces. This explains some of the failures that have been experienced in attempts to harness the energy available in the geothermal fields in the Imperial Valley of California, where much of the U. S. field effort in geothermal development is centered. Fortunately, despite the presence of dissolved salts, the fluids are usually chemically reducing, and severe corrosion rates can be avoided by the exclusion of air and by proper selection of materials of construction.

The exploration for geothermal energy is moving forward, with numerous examples of success. For example, the well known reserve in Imperial Valley has been estimated as sufficient to support the generation of 100,000 MW for 50 years of electricity (Ref. 5). The significance of this can be inferred from the rate of consumption of electricity in California, which was about 35,000 MW in 1973 (Ref. 6) (U.S. total: 300,000 MW (Ref. 7)). Other known U.S. reserves lie explored but dormant in the Mono-Long Valley area of California, in Beowawe, Nevada, and in Sandoval County, New Mexico, among others. These reserves are all liquid-dominated fields.

The NSF report Geothermal Energy (Grant GI-34313) anticipated the production of 395,000 MW from U.S. geothermal resources by the year 2000. However, this goal is attainable only with developments not yet achieved (Ref. 8). If the resources were largely vapor-dominated, the orderly development of the geothermal power industry would be assured. But it is the liquid-dominated fields which is prevalent, and the outlook for the geothermal industry is not clear. There is an acute need for a prime mover which can operate directly on the hot brine. Such a prime mover would almost certainly be the key to unlocking much of the treasure of geothermal energy in the U.S. and in other liquid-dominated fields all over the world.

II. HELICAL ROTARY SCREW EXPANDER

A 62.5-kVA prototype geothermal power plant utilizing a new helical rotary screw expander has been developed by Hydrothermal Power Co., Ltd. (HPC). The prototype plant has been tested and demonstrated by HPC for extended periods of time as a total flow wellhead system operating on hot untreated brine or brine and steam mixtures.

The helical rotary screw expander is a machine based upon development work conducted by Alf Lysholm in Sweden in the 1930's. By the 1950's Lysholm's machinery began to see extensive commercial application as a gas compressor. This application has had continued growth to the present date with installations involving 100 MW currently in operation. Early in 1971, HPC began development work in applying the Lysholm machine as a prime mover operating on geothermal hot water and brine. This development work has continued to the present.

The screw expander is a unique positive displacement machine, which bridges the gap between centrifugal or axial flow type aerodynamic machines and reciprocating positive displacement machines. It runs in a slower speed range without the high radial loads and balance problems characteristic of turbines.

As a geothermal prime mover, the helical screw expander is a total flow machine, which can expand directly the vapor that is continuously being produced from the hot saturated liquid as it decreases in pressure during its passage through the expander. The effect is that of an infinite series of stages of steam flashers, all within the prime mover. Thus, the mass flow of vapor increases continuously as the pressure drops throughout the expansion process, and the total fluid is carried all the way to the lowest

expansion pressure. The process approximates an isentropic expansion from the saturated liquid line for the total flow. The expansion within the machine can be illustrated with drawings such as Fig. 1. The geothermal fluid flows through the internal nozzle control valve and at high velocity enters the high-pressure pocket formed by the meshed rotors, the rotor case bore surfaces, and the case end face, designated by A in the two figures. As the rotors turn, the pocket elongates, splits into a V, and moves away from the inlet port to form the region designated by B. With continued rotation, the V lengthens, expanding successively to C, D, and E as the point of meshing of the screws appears to retreat axially from the expanding fluid. The expanded fluid at low pressure is then discharged into the exhaust port.

III. SCALE FORMATION, CORROSION, AND EROSION

Conditions for mineral precipitation from saturated brines within the expander occur for several interrelated reasons, including temperature decrease, pressure decrease, solvent removal, turbulence, and the presence of nucleation sites. The internal surfaces of the expander serve as mineral deposition sites. Mineral deposition on these surfaces provides several beneficial results. The thickness of the mineral layer increases until the rotor-to-rotor and rotor-to-case leakage clearances disappear and the mineralized surfaces are continually lapped; steady state is reached. The loss of leakage clearances results in substantial increase in the efficiency of the expander. This clearance removal mechanism will make possible the use of less expensive fabrication and machining procedures during manufacture, and also makes the expander self-healing in the event that scarring of the case or rotors should occur. Moreover, the mineral layer has been demonstrated to provide excellent protection of the case and rotors against corrosion. This protection will provide greater flexibility in the selection of relatively low-cost materials of construction. Similarly, there has been no evidence of erosion, either because the scale layer forms a protective coating or because the fluid velocities within the machine are not high, or both. The effects of much higher velocities by nozzling at the inlet are still to be determined for the high-pressure fields.

The lapping process associated with the minerals which are deposited on the machine surfaces within the expander is a source of suspended nuclei for additional mineral deposition and crystallization within the brine. These nuclei supplement those which form spontaneously throughout the brine in the flashing turbulent conditions within the expander. In an experimental investigation of mineral deposition carried out in October 1971, while operating a helical screw expander on Well M-10 at Cerro Prieto, HPC observed that mineral deposition occurred either almost exclusively within the expander or on the seed particles traveling with the exhaust brine. After 307 hours of operation, the deposits ranged from 5/32 in. at the expander exhaust port to 1/64 in. 50 feet downstream. In the absence of the expander, the same well and feedline plugged shut a 12-in. diameter exhaust pipe in 72 to 96 hours. An expander with an insufficient expansion ratio was used in this investigation, and some flashing occurred in the exhaust port. The present prototype expander features a larger expansion ratio so that very little flashing has occurred in its exhaust port; no scale deposit problem has been detected during over 1000 hours of testing. This characteristic of mineral

precipitation occurring preferentially within the expander, either on the expander surfaces which are self-cleaning or harmlessly in suspension, is highly beneficial. The tendency to deposit scale downstream appears to be negligible, at least along an isothermal path. This is important for inter-staging as well as in waste lines.

IV. EXPANDER ENGINE EFFICIENCY

Performance tests of the 62.5-kVA prototype HPC geothermal power plant were performed August 21, 1974, on brine from Well 6-1 at the U. S. Bureau of Reclamation geothermal test facility on the East Mesa KGRA. The two tests gave results of 65 and 74% for the expander efficiency compared with an ideal machine. The test results should be considered preliminary since no attempt was made to optimize the operating conditions or the test set-up. (A report of the details of the tests is in preparation.)

Industrially, the helical rotary positive displacement machine is widely used to compress air, nitrogen, hydrocarbons, and a variety of refrigerants. As expanders, these machines are used as prime movers, accessory power drives, and for temperature reduction in gas cycle refrigeration systems. They have been demonstrated to have overall adiabatic efficiencies typically well in excess of 70% over a wide operating range and as high as 85%.

An essential to high engine efficiency is small leakage past the rotors. This requires small clearances, both rotor-to-rotor and rotor-to-case. The minute clearances brought about the wet lapping of the mineral deposits in the geothermal expander may lead to the maximum efficiencies in this new unique application.

V. SYSTEM EFFICIENCY

Three energy conversion concepts -- the Flashed Steam System, the Binary Cycle System, and the Total Flow System -- are present contenders for producing electricity from hot-water geothermal resources. In the Total Flow System, as represented by the Helical Rotary Screw Expander Power System, the hot wellhead product follows on isentropic expansion directly from the wellhead through a two-phase expander to the exhaust pressure and temperature. This system is thermodynamically the simplest and is theoretically optimum. In several excellent papers (Refs. 9-11), it has been estimated that the Total Flow System offers a 60% efficiency gain over the other two, assuming that all systems have a 70% engine efficiency. The engine efficiencies of greater than 70%, which seem assured for the helical rotary screw expander, will give the Screw Expander System an added advantage. Moreover, the estimated 60% efficiency gain is conservative, resulting from optimistic assumptions including, for example, achieving 70% of the Carnot efficiency for the secondary loop of the Binary Cycle System, and perfect steam separation in the Flashed Steam System. Actual field experience to date indicates an efficiency advantage of considerably greater than 60% for the Helical Rotary Screw Expander Power System operating on high enthalpy brines.

VI. PROPOSED EVALUATION PROJECT

A project plan has been prepared by the Jet Propulsion Laboratory for the evaluation of the Helical Rotary Screw Expander Geothermal Power System jointly by JPL and HPC. This plan has been submitted to the Division of Advanced Energy Research and Technology of the National Science Foundation for consideration in the NSF/RANN FY 1975 geothermal program.

Initially, a modular 1250-kVA geothermal power plant incorporating an HPC Lysholm-type helical rotary screw expander as the prime mover will be constructed and then operated on total flow brine to evaluate its mechanical and thermodynamic performance. In the initial work the prime mover will be single stage, expanding to atmospheric pressure or above. Studies of its interactions with the well and an electrical grid system are planned as well as an assessment of brine scale formation, corrosion, erosion, vibration, endurance, and other mechanical problems. The work will lead to design and cost studies of a broad range of applications followed by the testing and evaluation of a completely automated versatile pilot mini-plant of 5 to 7 MW for wellhead siting in liquid-dominated fields.

Hydrothermal Power Co., Ltd. will build the 1250-kVA power system model. The ensuing research will be carried out by the Jet Propulsion Laboratory and the Hydrothermal Power Co., Ltd., first using low-saline high-enthalpy brine from an area to be selected as part of the project, and subsequently utilizing hypersaline brine in the Imperial Valley, California. It is anticipated that the brine-producing agencies or site operators will participate in the research at no cost to the project. The possibility of additional mutually beneficial research activities to be carried out jointly with other organizations as part of the project on a similar basis will be explored early in the project.

The overall project is planned in five phases to be managed by JPL in approximately the following sequence as shown in Fig. 2: (1) project presentation, power system module construction, test site selections, and research planning and preparation; (2) power system characterization and evaluation; (3) longevity testing and interaction studies with the producing well and an electrical grid system; (4) applications systems studies; and (5) design, construction, testing, and evaluation of the pilot mini-plant.

The research is expected to provide the performance maps for this new equipment application for the wide range of conditions which might be found in liquid-dominated geothermal fields. It will deal with the questions of performance optimization, expander staging, effects of brine quality and non-condensables, sink pressure and temperature, brine management, waste disposal, noise, equipment size, and costs. It will aim at optimum exploitation of the resource. The concept of the wellhead power plant will be examined in detail.

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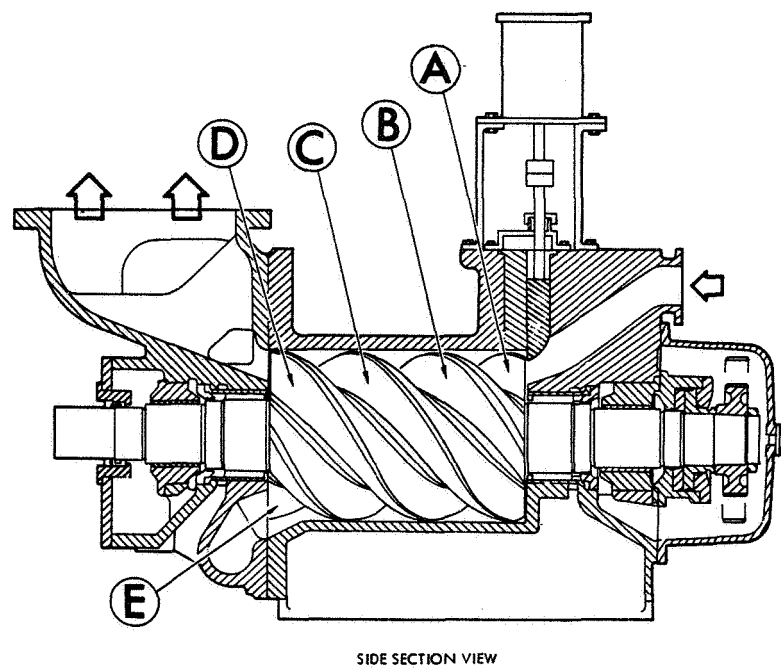
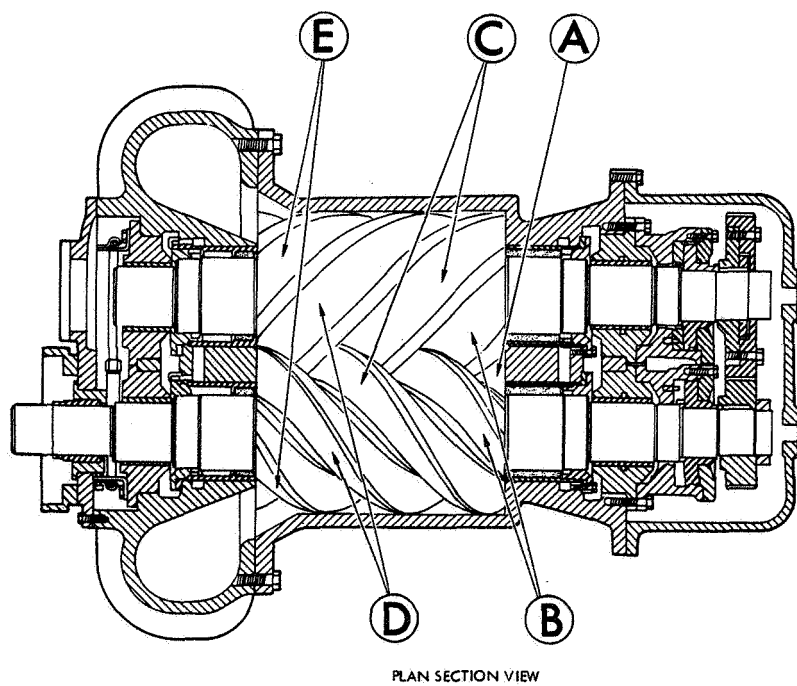


Fig. 1. Helical rotary screw expander

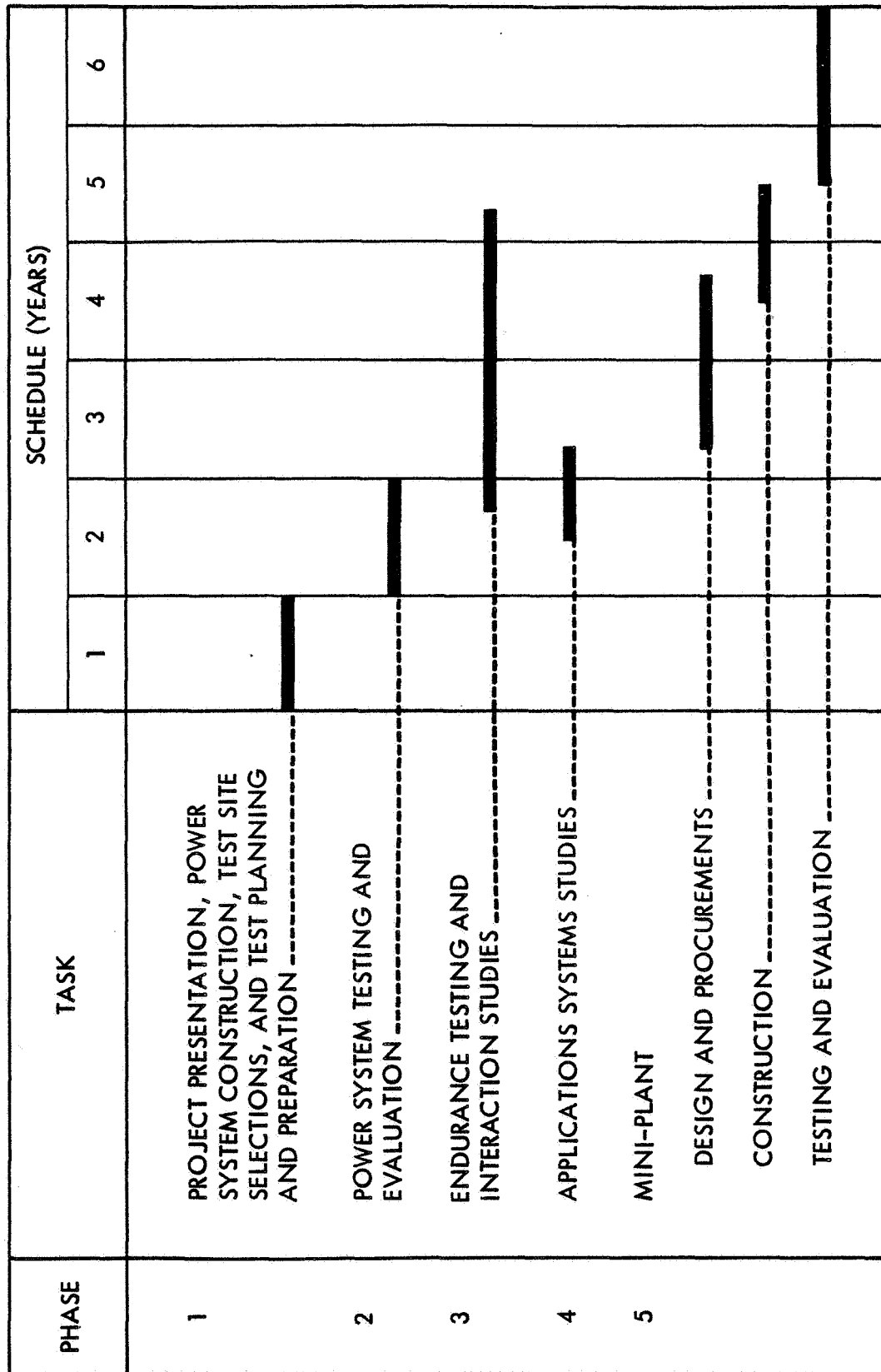


Fig. 2. Total project outline

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ELECTRIC POWER GENERATION USING
GEOTHERMAL BRINE RESOURCES
FOR A PROOF-OF-CONCEPT FACILITY

J. W. Hankin
Bechtel Corporation
San Francisco, California

An exploratory systems study of a geothermal proof-of-concept facility is being conducted. This study is the initial phase (Phase 0) of a project to establish the technical and economic feasibility of using hot brine resources for electric power production and other industrial applications. Phase 0 will include the conceptual design of an experimental test-bed facility and a 10-MWe power generating facility.

Bechtel Corporation is performing an exploratory systems study of a geothermal proof-of-concept facility under a National Science Foundation grant. This study is the initial phase, Phase 0, of a project to establish the technical and economic feasibility of utilizing hot brine resources, presently undeveloped in the United States, for electric power production and other industrial applications. The Phase 0 study began on July 1, 1974, and is scheduled to be completed by January 31, 1975.

The National Science Foundation's purpose in sponsoring this project is to promote the development of geothermal technology and effect its transfer to the private sector of the economy. Subsequent phases of the project, not included in the present study, will entail engineering and construction of the proof-of-concept facilities.

Phase 0 will include the conceptual design of an experimental "test-bed" facility and a 10-MWe power generating facility. A specific geothermal site will be selected and used as the basis for developing and illustrating the concepts involved in the design. An objective of the study is to determine the earliest feasible time that these facilities could be in operation. Accordingly, the site will be one at which hot brine resources have previously been identified. This will eliminate the time-consuming effort that would otherwise be needed for exploration.

The experimental facility will be designed to serve as a test bed for developing advanced geothermal processes and equipment. Offices, laboratories, and test areas that are necessary to support the test programs and evaluate the resulting data will be included. The capability will be provided to test energy conversion equipment, such as heat exchangers and multiphase turbines, with geothermal fluid under operating conditions. Provisions will

also be made for concurrently carrying out other test programs, such as methods for controlling corrosion, erosion and scaling, and nonelectric uses of geothermal energy.

The thermodynamic performance of several energy conversion processes will be evaluated and the most promising selected for use in the 10-MWe power generating facility. The process selected will depend to a large extent on the chemical and thermodynamic characteristics of the geothermal fluid at the site used to illustrate the concept, as well as other site-sensitive conditions, such as the availability of cooling water and environmental effects.

The conceptual design will include all engineering drawings and equipment lists necessary to support an order-of-magnitude capital cost estimate. The output from Phase 0 will also include a plan for carrying the project forward through the detail design, construction, and startup phases. The plan will comprise a delineation of the scope of work and a time schedule.

The Phase 0 study will be completed by preparing a final report containing a record of the study findings and data of permanent value.

PHASE 0 STUDY FOR A GEOTHERMAL SUPERHEATED
WATER PROOF-OF-CONCEPT FACILITY

R. H. Douglass and R. O. Pearson
TRW Systems Group
Redondo Beach, California

The TRW Systems and Energy organization is performing a Phase 0 study under a grant from the National Science Foundation. The Phase 0 study is directed to the selection of a representative liquid-dominated geothermal resource of moderate salinity and temperature, selection and conceptual design of a nominal 10-MWe energy conversion system, and implementation planning for Phase 1: Subsystem (component, experiments) and Phase 2: Final design, construction, and operation of experimental research facilities.

The objective of the overall program is to demonstrate the technical and economic viability of utilizing moderate temperature and salinity liquid-dominated resources with acceptable environmental impact, and thus encourage commercial scale development of geothermal electrical power generation. Inasmuch as the stimulation of commercial investment is a fundamental program objective, expert advisors were invited from municipal and public owned utilities and the Sierra Club who have participated in planning sessions and design reviews. The advisors include H. Hess (Sierra Club), T. Hinrichs (SDGE), L. Rasband (SCE), E. Ross (City of Riverside) and J. Woodburn (City of Burbank). The advisor's identification of development risks and economic and environmental requirements has beneficially enhanced the project planning and design decisions. Also the TRW technical resources have been extended by the retained services of recognized geothermal consultants Doctors J. Combs, G. Keller, L. Handy, and Rogers Engineering Co. adding the benefits of their experience and judgment to assuring project technical viability (Fig. 1).

The overall project is aligned to the RANN phased project planning approach as follows:

- (1) Phase 0: Advanced Research and Systems Analysis
 - (a) KGRA assessment, evaluation, and site selection.
 - (b) Energy conversion candidate assessment and concept selection.
 - (c) Conceptual design, requirements specification, and critical technology identification.

- (d) Phase 1 and preliminary Phase 2 implementation planning.
- (e) Utilization planning.
- (2) Phase 1: Systems Definition and Subsystem (Component) Testing
 - (a) Drilling and proving out wells.
 - (b) Experimental test bed development.
 - (c) Critical component testing.
 - (d) Phase 2 implementation planning.
- (3) Phase 2: Final Design, Construction and Operation of Experimental Research Facilities
 - (a) 10-MWe (nominal) power plant.

The project status to date includes the selection of the East Mesa, California, anomaly as a representative moderate temperature (350°F) and salinity (3000 to 25,000 ppm) resource. The project site selected is adjacent to the Bureau of Reclamation desalting experimental facilities. Energy conversion cycle concepts being analyzed and evaluated, to utilize this resource, are single- and two-stage flashed steam, binary and hybrid dual (flashed steam and binary). System selection will be finalized by October 15, and Phase 1 and 2 implementation planning will be completed in December 1974 (Fig. 2).

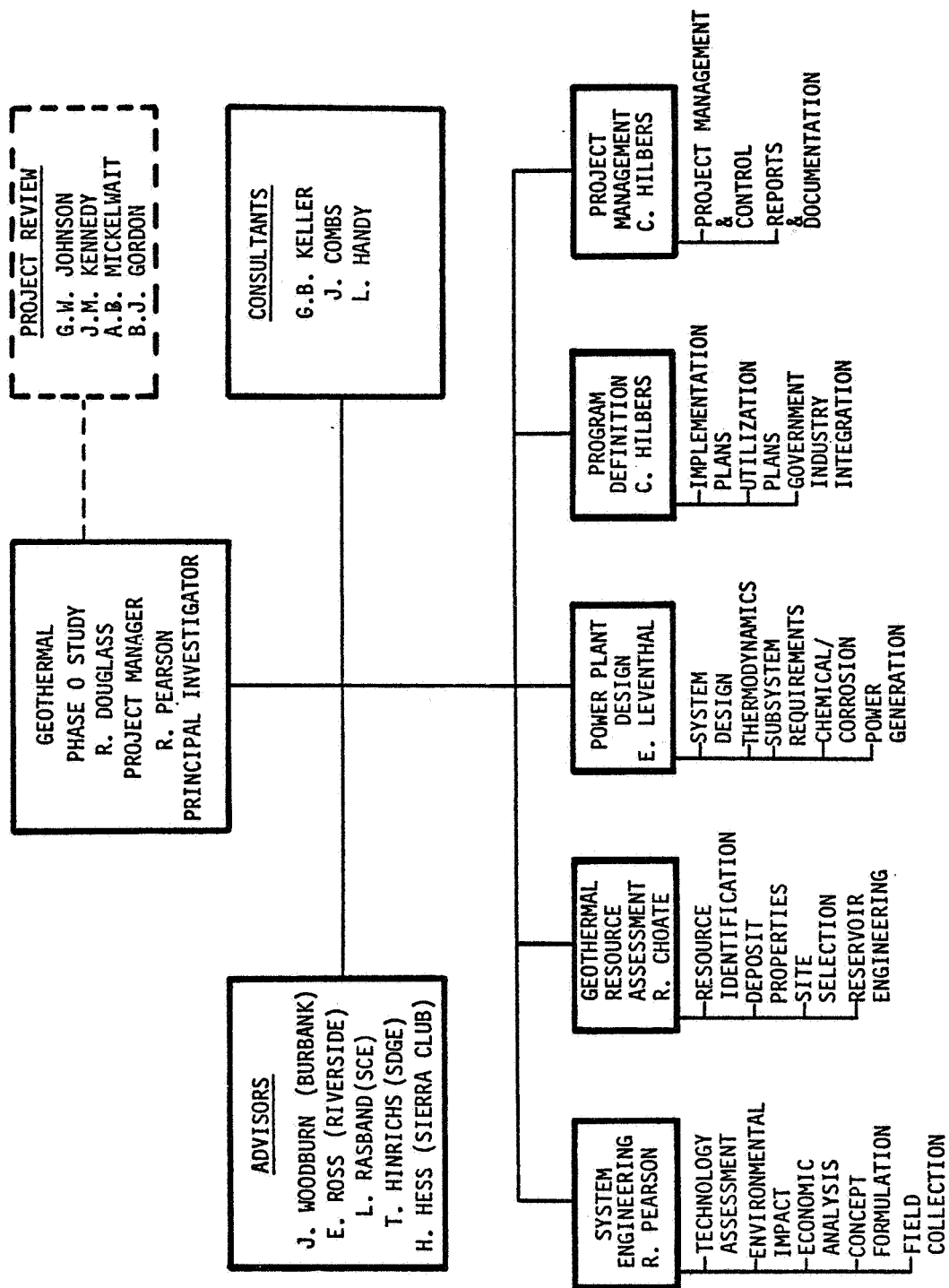


Fig. 1. Geothermal Phase 0 study functional organization

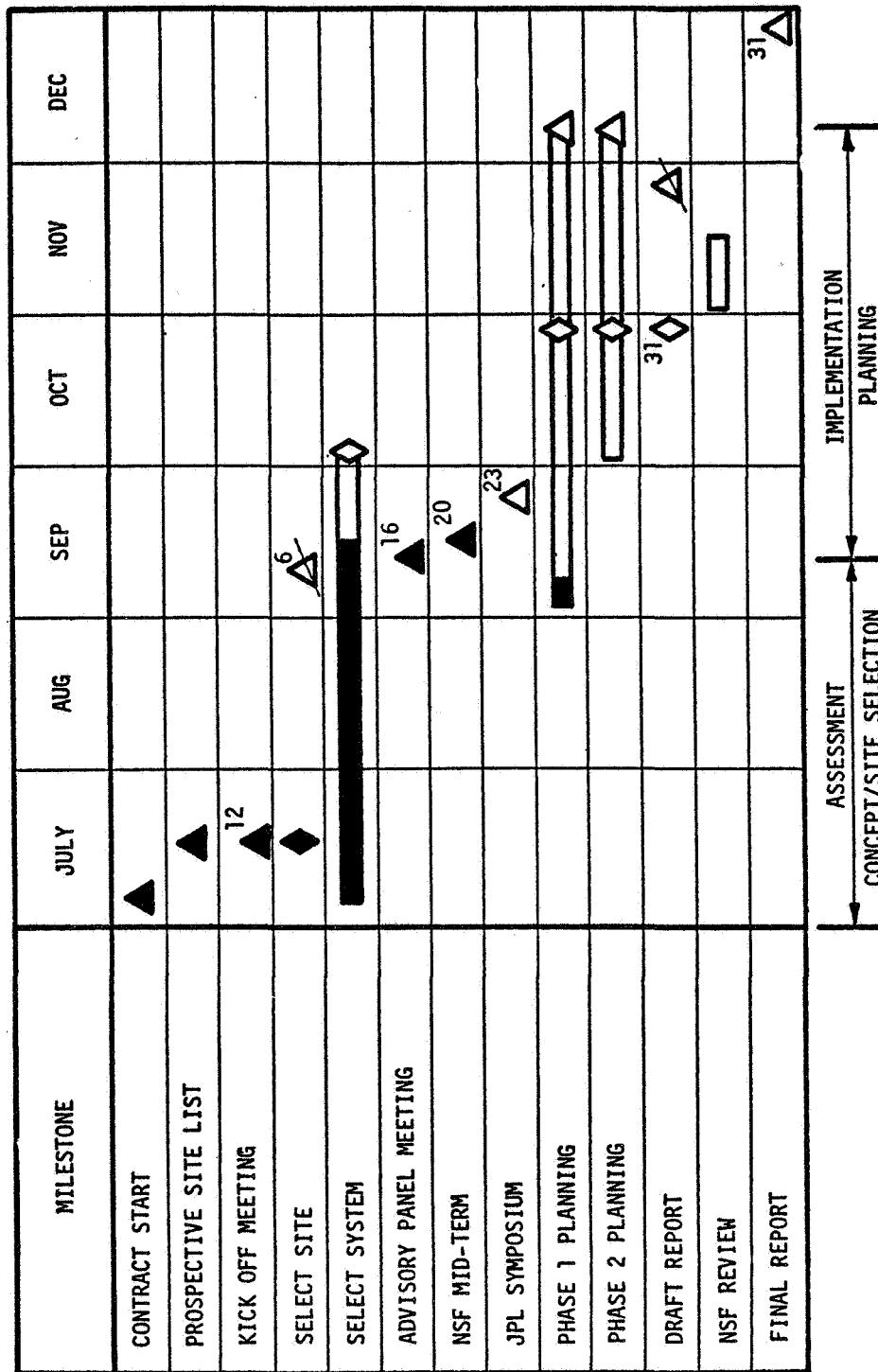


Fig. 2. Geothermal Phase 0 schedule

SESSION VI

PANEL SESSION

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SESSION VI. PANEL SESSION

SESSION CHAIRMAN: R. B. Coryell

THE HYDROGEN SULFIDE EMISSIONS ABATEMENT PROGRAM
AT THE GEYSERS GEOTHERMAL POWER PLANT –
G. W. Allen and H. K. McCluer

COMBINING TOTAL ENERGY AND ENERGY INDUSTRIAL
CENTER CONCEPTS TO INCREASE UTILIZATION EFFICIENCY
OF GEOTHERMAL ENERGY – B. P. Bayliss

COOPERATIVE EFFORTS BY INDUSTRY AND GOVERNMENT
TO DEVELOP GEOTHERMAL RESOURCES – D. R. Butler

A CITY INVESTS IN ITS FUTURE – J. N. Baker

GEOTHERMAL STEAM CONDENSATE REINJECTION –
A. J. Chasteen

UTILITY COMPANY VIEWS OF GEOTHERMAL DEVELOPMENT –
T. C. Hinrichs

A NEED FOR FOCUSING GEOTHERMAL RESEARCH AND
DEVELOPMENT EFFORTS – D. F. Spencer (abstract only)

THE HYDROGEN SULFIDE EMISSIONS ABATEMENT PROGRAM
AT THE GEYSERS GEOTHERMAL POWER PLANT

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San Ramon, California

This paper describes the scope of the hydrogen sulfide (H_2S) abatement program at The Geysers Geothermal Power Plant and the measures currently under way to reduce these emissions. The Geysers steam averages 223 ppm H_2S by weight and after passing through the turbines leaves the plant both through the gas ejector system and by air-stripping in the cooling towers. The sulfide dissolved in the cooling water is controlled by the use of an oxidation catalyst such as an iron salt. The H_2S in the low Btu ejector off gases may be burned to sulfur dioxide and scrubbed directly into the circulating water and reinjected into the steam field with the excess condensate. Details are included concerning the disposal of the impure sulfur, design requirements for retrofitting existing plants and modified plant operating procedures. Discussion of future research aimed at improving the H_2S abatement system is also included.

I. INTRODUCTION

While geothermal energy has been developed for the production of electric power in several locations throughout the world, the only commercial development in operation in the United States is at The Geysers, about 80 miles north of San Francisco. From Pacific Gas and Electric Company's initial 12 megawatt (MW) unit, which commenced operation in 1960, nine additional units have been constructed. The total capacity is now 396 MW, which makes The Geysers the largest geothermal electric power plant in the world. Design and construction presently under way will increase net output to about 900 MW by the end of 1977. There are plans for continuing expansion as steam reserves are proven and developed. The facilities and operations at The Geysers Power Plant have been well described previously (Refs. 1 through 4). Thus, only those aspects pertinent to the hydrogen sulfide emissions abatement program will be discussed herein.

In contrast to most of the world's geothermal resources, the wells at The Geysers produce slightly superheated steam. This steam contains small amounts, usually less than 1 percent by weight, of noncondensable gases, mostly carbon dioxide. The ranges of concentrations of the noncondensable gases

measured at The Geysers are presented in Table 1. These gases are natural components of the atmosphere, and their concentrations that we have measured in ambient air at The Geysers are not considered harmful. However, hydrogen sulfide (H_2S) is an air pollutant that P G and E, or any other user of geothermal steam, is required to control under regulations of the State of California Air Resources Board (ARB) and also the local air pollution control districts (APCD). The APCD regulations applicable at The Geysers generally state that no single emission source shall exceed 1000 parts per million by volume (ppm_v) of any sulfur compound expressed as sulfur dioxide (SO_2). The ARB H_2S standard is 0.030 ppm_v for ambient air. Since this concentration is approximately the odor threshold for H_2S , as a rule of thumb one can say that if one can smell H_2S , the ARB standard is being exceeded.

The generating units at The Geysers use slightly superheated steam at about 100 psig, and after passage through the turbine, the low pressure steam is condensed in direct contact condensers operating at 3-5 inches of mercury, absolute. Figure 1, the power cycle diagram for the proposed Unit 15, is typical of the units of The Geysers. Most of the noncondensable gases in the steam are continuously removed from the condenser by the two-stage gas ejector system and are vented to the atmosphere through stacks from 60-85 feet above ground level, depending on the unit. However, since the steam contacts the cooling waters directly in the condenser, about two-thirds of the H_2S dissolves in the cooling waters and is then carried to the cooling tower.

The cooling waters, in passing through the cooling tower, are partially air-stripped, so the tower exhaust air contains on the order of one ppm_v H_2S . Some of the H_2S (on the order of 30 percent) is naturally oxidized to elemental sulfur in the cooling tower and eventually returns to the steam field with the surplus condensate. Though the emissions from the cooling towers are well within permissible levels, it is still desirable to minimize these emissions from the power generating units to reduce the H_2S concentrations in the ambient air outside of The Geysers Power Plant. Thus, P G and E's H_2S emissions abatement program included the releases from both the gas ejector stacks and the cooling towers.

II. DESCRIPTION OF THE ABATEMENT PROGRAM

P G and E began investigating methods to control the H_2S emission from The Geysers Power Plant in 1971. These investigations have included literature searches, parametric evaluations, bench-scale testing (both in the P G and E laboratories at the Department of Engineering Research and at The Geysers), and, at the present time, unit-scale testing at Units 1, 2, and 4.

A. Cooling Tower Emissions

The bench-scale testing at The Geysers investigated four methods to control the emissions from the cooling towers by reacting the H_2S to elemental sulfur (S^0) in the water phase before it could be air-stripped. These were:

- (1) Direct injection of SO_2 into the cooling waters to oxidize the H_2S to S^0 by the Claus reaction



- (2) Simultaneous injection of both SO_2 and air.
- (3) Addition of a metal catalyst, iron, to the cooling waters to promote direct oxidation of the H_2S to S^0 by the oxygen dissolved into the circulating cooling waters in the cooling towers:



- (4) Addition of Cataban, a chelated iron compound manufactured by the Rhodia Corporation, to catalyze the direct oxidation of H_2S by the dissolved oxygen.

All four of these methods reduced the H_2S emissions from the bench-scale test apparatus. The third approach, addition of a metal catalyst to the circulating cooling waters, was chosen for unit-scale testing, since this method appears to be best adapted for operations at The Geysers Power Plant. The majority of the tests of methods to control cooling tower H_2S emissions are being made at Units 1 and 2. These two units, of nominal generating capacities of 12.5 and 14 MW, are the oldest and smallest of all the units installed at The Geysers. However, their design and layout are similar to all subsequent units in operation. This permits us to scale up to any desired size with a high degree of confidence. A program to study corrosion by the metal-containing condensate is also underway at Unit 1 (Ref. 5).

Several different metals will catalyze the oxidation of H_2S in the water phase (Ref. 6). Three of these were experimentally investigated at The Geysers: iron, nickel, and copper; copper was the least effective of the three. It was found that iron concentrations of approximately 30 mg/l and nickel concentrations of 1.5 to 2 mg/l could reduce the total H_2S emissions from the cooling towers by 90 percent or more. The choice between these two oxidation catalysts is now a matter of relative economics and their effects, if any, on the long-term operation of the units. Preliminary results from the long-term testing of the iron oxidation catalyst at Unit 1 have shown that there is a definite increase in the corrosion rate for this unit. The overall effect that this may have on equipment service life is still under evaluation. Additional corrosion rate monitoring equipment is being installed to expedite the testing of alternate catalysts and the effectiveness of corrosion inhibitors.

The use of the metal catalysts markedly increases the suspended solid content of the circulating waters, both from the catalyst itself and the elemental sulfur which is produced. Work has been done on minimizing the solids buildup in the cooling tower basin and in removing these solids from the excess condensate that is returned to the steam field. The method of choice at this time is rapid sand filtration. Pilot tests have shown that sand filtration can remove more than 90 percent of the suspended solids and perform consistently with little attention, an important factor in The Geysers' operation.

B. Gas Ejector Emissions

Two methods to control the emissions of the H_2S in the noncondensable gases vented from the gas ejector system are still under evaluation. In one method, the H_2S is burned to SO_2 which is then scrubbed into the cooling waters to maintain the SO_2 concentration in the products of combustion that would be vented to the atmosphere below the 1000 ppm_v regulation. The noncondensable gases will burn since they contain enough methane and hydrogen to sustain combustion (150-200 Btu/cu ft). The SO_2 scrubbed into the circulating waters eventually either is injected into the steam field or it can be neutralized with lime if the waters are too acidic for the reinjection well casing or cooling water system components. The marginal flammability and pulsating nature of the gases from the ejectors posed some challenging engineering designs. However, a full-scale burner/scrubber system has been designed for Unit 4 (26 MW). An oxidation catalyst feeder system and a sand filtration system have also been engineered for the tests at Unit 4, incorporating all the design features to date, and construction has started. The data obtained at this unit will be used in the design of a full-scale abatement system for Unit 11 (106 MW).

In the other method, H_2S emissions from the ejectors are controlled by scrubbing the noncondensable gases with a water solution containing a metal catalyst so that the H_2S is dissolved and oxidized to S^0 . Tests of the H_2S scrubbing method will also be performed at Units 1 and 2 this year.

C. Sulfur Disposal

The solids collected in the rapid sand filter include elemental sulfur with some metal catalyst and fine rock dust carried up the well by the steam. Studies show that it is not economical to refine the recovered sulfur to commercial purity; the cost of the refined sulfur from The Geysers would be higher than that of byproduct sulfur from natural gas desulfurization plants. To date we have not produced large enough quantities of the solids to evaluate their possible direct application to soils or conversion to sulfuric acid for fertilizers. Other practical applications will also be considered. Until a practical application for these solids can be developed, it is planned to dispose of the solids in a landfill. P G and E has retained a consulting firm to evaluate the feasibility of constructing a landfill disposal site at The Geysers for these solids. Should it be necessary to neutralize the cooling waters that have been used to scrub out the SO_2 from burning H_2S in the noncondensibles, the calcium sulfate/sulfite formed would also be disposed of in the landfill.

III. CONCLUSIONS

We expect that the control methods described herein will reduce the H_2S emissions from a unit to permissible levels and will control them so that they alone will not exceed the ARB ambient air quality standard for H_2S at ground level beyond a few hundred feet from a unit. In anticipation of a period of successful test operation this year, a program for installing H_2S control equipment on ten existing units, as well as future units, has been proposed to regulatory agencies.

It should be noted that the control methods described above were selected on the basis of our existing knowledge and experience; they are not necessarily the optimum that could ultimately be developed for use at The Geysers. There is considerable effort in progress in the world today on the development of processes and equipment to control emissions of sulfur compounds from industrial equipment. Thus, we anticipate that further research will be performed on H₂S emissions control at The Geysers. One area of interest that we now see is the addition of nonmetallic catalysts to the circulating cooling waters. A second area of interest is the removal of the H₂S from the steam upstream of the turbine. However, the control methods described herein should provide the necessary H₂S emissions control for further development of this important, nonfossil-fueled power generating resource.

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PERFORMANCE	
THROTTLE FLOW	1,073,800 S
GENERATOR ELECT. OUTPUT	60,000 MW
AUXILIARY POWER (ELECTRICAL):	
CONDENSATE PUMPS	900 kW
COOLING TOWER FANS	625 kW
OTHER	175 kW
TOTAL:	2000 kW
NET UNIT OUTPUT	58,000 kW
NET INPUT	1,355,000,000 BTU/HR.
NET HEAT RATE	33,360 BTU/kw hr.
CONDITIONS	
GENERATOR POWER FACTOR	0.90
TURBINE EXHAUST BACK PRESSURE	4" Hg
DRY BULB AIR TEMPERATURE	80F
WET BULB AIR TEMPERATURE	65F
NOTE: ALL STEAM FLOWS INCLUDE 1.0% NON-CONDENSABLE GASES	
LEGEND	
--- (solid line)	MAIN STEAM LINE
--- (dashed line)	STEAM LINE
--- (dotted line)	WATER LINE
--- (dash-dot line)	GAS LINE
S	LBS/HR. OF STEAM
M	LBS/HR. OF WATER
G	LBS/HR. OF GASES
F	DEGREES FAHRENHEIT
H	ENTHALPY OF STEAM (BTU/LB)
A	ABSOLUTE PRESSURE (PSIA)

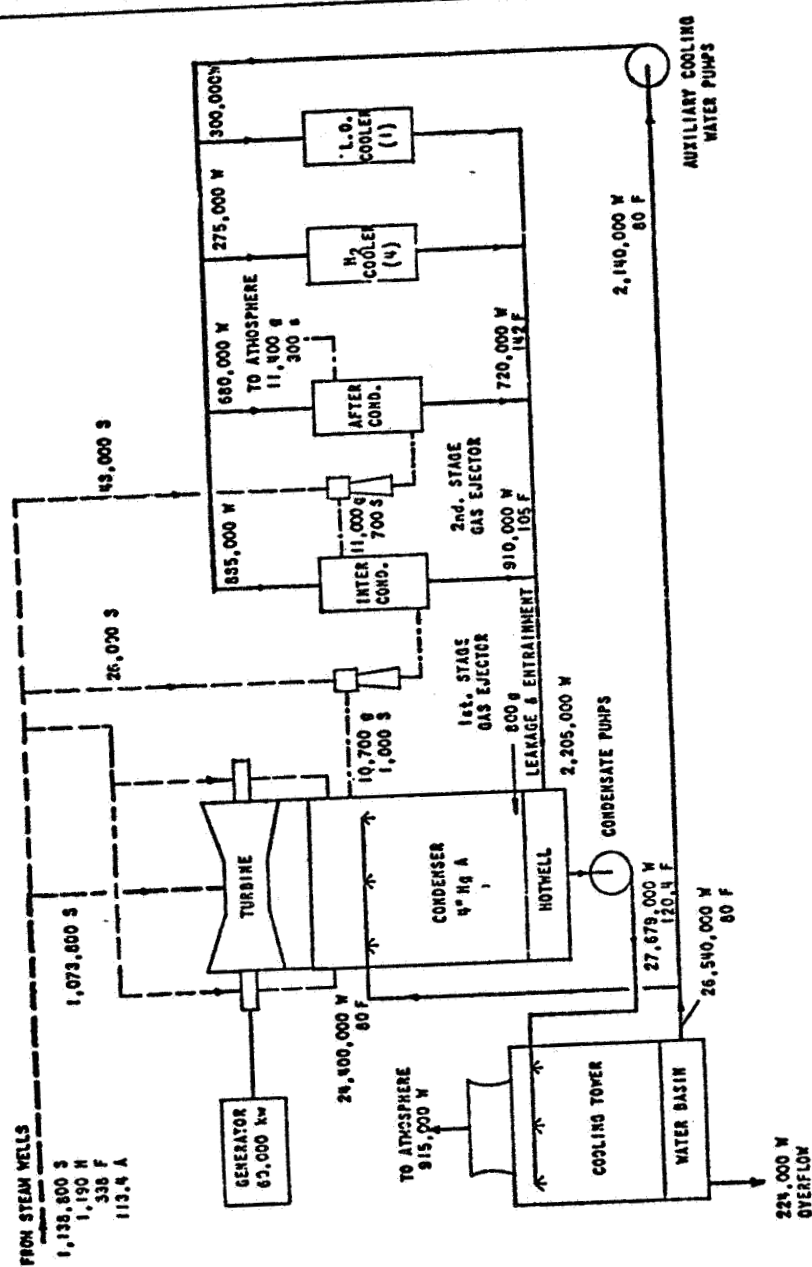


Fig. 1. Unit 15 power cycle

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COMBINING TOTAL ENERGY AND ENERGY INDUSTRIAL
CENTER CONCEPTS TO INCREASE UTILIZATION
EFFICIENCY OF GEOTHERMAL ENERGY

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Lloyd Corporation and Magma Energy, Incorporated
Los Angeles, California

Integrating energy production and energy consumption to produce a total energy system within an energy industrial center would result in more power production from a given energy source and less pollution of the environment. Strong governmental support would be required for the crash drilling program necessary to implement these concepts. Cooperation among the federal agencies, power producers, and private industry would be essential in avoiding redundant and fruitless projects, and in exploiting most efficiently our geothermal resources.

I. INTRODUCTION

The United States and indeed the World is in deep trouble these days on a number of fronts. In the forefront is the projected gap between energy supply and consumption. This is a frightful gap to behold and one which holds the seeds of a demoralizing and humiliating decline in mankind's vaunted "ever onward and upward" climb towards its ultimate star of destiny.

It is required that advances be made on two fronts — first we must increase our energy output some orders of magnitude by augmenting known means and creating new means of supplying additional energy.

A second imperative is to utilize, in the most efficient way, that geothermal energy which is made available for power generation.

II. NEAR-SITE ENERGY CONSUMPTION

The very organization responsible for this Conference, The National Science Foundation, also sponsors an Industrial Center Study, managed by Dow. It concerns itself with, among other things, two fundamental considerations of energy utilization efficiency. First is the advantage of physical placement of the industrial consumer of electricity (chemical plants for example) close to the origin of production (a geothermal plant for example). Second is the utilization of exhaust steam from turbines for industrial process use. Under this system, industrial boilers are eliminated and the needs for cooling towers, condensers or cooling ponds to dispose of heat is reduced.

Of course, these economies have another inherent advantage: — with more power being produced from a given energy source, less environmental pollution will result!

The author applauds NSF authorization and sponsorship of this study, originally submitted to it by Governor Milliken's Michigan Special Commission on Energy.

III. TOTAL ENERGY CONCEPT

To carry the foregoing Energy Industrial Center Study one step further, the author believes the Total Energy system concept could be applied here. Mr. Fred Dubin, head of a New York consultant firm states in his article "Total Energy Systems and the Environment";

"Integrating systems may become an important factor in conserving the nations natural resources. Spectacular savings in energy can result from this concept. In this "systems" approach conversion of fuels (including geothermal fluids) to electric power is only one segment of the system. The transmission and distribution systems and the utilization of "thermal waste" are important factors. Design of end-use facilities, marriage of sewage treatment plants with solid waste disposal systems, integrating lighting systems with heating and cooling systems, design of exhaust-air systems and fresh air intake systems to permit energy transfer to take place, are only a few examples of the "Total Energy approach. "

Total Energy has been called an energy-recovery system using the waste heat from the generation of electricity. Of course, it is more than this. A total resource system certainly offers significant opportunities for conservation of energy and does require the coordinated effort and understanding of all disciplines. Revising rigidly inflexible municipal codes for example, to permit use of new methods and systems without sacrificing safety, is badly needed.

It is believed that Federal and State studies to implement the Total Energy concept would be money and time well spent. It is easy to visualize how the Geothermal Energy Industry could participate in and benefit from such a basic concept.

Still on the broad subject of energy efficiency the question is posed: Can Federal programs aid in the research of means to increase cycle efficiency (heat rate) in geothermal power plants and implement usage of resulting improvements with the steam utility companies? Is there any possible way to beneficially increase the enthalpy of the natural steam entering the plant for a net increase in kW output of the plant or is this an impossibility like perpetual motion or bootstrap lifting?

IV. GOVERNMENTAL ASSISTANCE

The author read with a great deal of interest Dr. John D. Ridge's idea that he presented at USGS symposium during the recent dedication of its National Center at Reston, Va. He proposes a cross-country checkerboarding of the conterminous U.S. with 7500 wells on 20 mile centers, each 15,000 feet deep, to "uncover \$750 billion of recoverable raw materials at a project cost of \$3 billion." The entire oil industry drills annually in this country about 25,000 to 30,000 wells for oil and gas at an average depth of just under 5,000 feet. But they do it selectively. The author has been involved in deep oil well drilling for 20 years and even though the drilling program that Dr. Ridge advances is manifestly impractical, the idea behind his idea is quite pertinent and practical. He is an advocate of direct field exploration. As a recommendation change the depth to 2500 feet; the spacing between wells to one mile; be selective as to the areas approved for checkerboarding — generous, but selective —; and his idea could then be considered as an intelligent, direct-type of practical exploratory action having an honest chance of paying handsome dividends.

As to other assistance that Governmental agencies could render the private sector of the geothermal energy industry perhaps number one would be assistance in the environmental fight: As it now stands, compliance with full detailed environmental requirements has the effect of seriously delaying the contributions of geothermal to the energy shortage and of greatly increasing costs. Mr. Aidlin discusses this problem:

"To determine the extent of readily useable geothermal energy as quickly as possible I suggest the following:

- (1) Permit through 1975 the drilling of an exploratory well and not more than two confirmation wells in any area, without requiring compliance with full, detailed environmental requirements. It seems unrealistic that expensive, time consuming effort be devoted to environmental studies and reports before it is even known whether or not the resource will be found in economically useable quantity or kind.
- (2) If a useable geothermal energy resource is found, then the requirement for more detailed environmental studies may be made applicable, if the community deems that desirable.
- (3) If the developer is unable or unwilling to conform to appropriate environmental constraint for further development, he should be permitted to surrender or abandon the project and to write off as a loss two times the entire cost of the project. The reason for permitting the loss write off is to encourage the developer to take the risk of the initial geothermal well or wells to determine the presence of the resource rather than to spend his capital in other less risky pursuits.
- (4) The developer desiring to operate under this program should, of course, be required to disclose pertinent data to the appropriate governmental agency concerned with energy planning.

This program will require, strong government support to make available the casing, equipment, drilling rigs and other materials required for a crash drilling program.

It has the advantage of permitting rapid drilling of presently known promising areas, so that the energy planners will know what they can count on; and while it bypasses stringent, time-consuming environmental requirements on a temporary basis it does not supersede them. "

The appropriate federal agencies could also help stimulate development by incentives as set forth by Mr. Aidlin:

"For this program to produce greater results it will be necessary also that the Internal Revenue Service reverse its present policy which clearly discriminates against geothermal resources and unnecessarily and unreasonably impedes its development.

Additionally, the Bureau of Land Management will have to adopt policies which better accord to the wildcatter the fruits of his effort and risk. If an operator is willing to test an area at his expense but does not have enough land around it to make the investment economically sound, if the adjoining land is federal land, the BLM should make available a reasonable amount of its land for lease to the wildcatter, if his well develops a viable geothermal resource. "

To accelerate utilization of geothermal resources in generation of electric power, Mr. Aidlin suggests the following:

"In order to demonstrate the economic and mechanical viability of the binary cycle, electric generating system, which system is generally accepted as the only readily available and most likely to succeed, the Federal government, through one or more of its agencies, should guarantee loans for construction of two or more small capacity binary cycle plants - that is, from approximately 10 to 50 megawatts capacity - to generate and sell electricity on a commercial basis. The purpose would be to demonstrate to the utilities that such plants are economically and technologically sound. Such plants in commercial operation would provide the kind of operational and economic information that cannot be obtained in the laboratory.

If such plants operate profitably there will have been no cost to the government, and the technology will have been demonstrated. If they do not operate profitably, information will be gained which may correct errors or technological defects.

By guaranteeing such loans the government will have enabled the utility to proceed with power generation without first assuring itself of the life and extent of the resource reservoir beyond its ability under present technology to do. In other words, while we are developing better reservoir analysis and measuring techniques, we will be generating electric power for use. "

V. ENVIRONMENTAL CONSIDERATIONS

Although the final subject is admittedly somewhat critical in its nature, it is offered with no apology as the remarks are intended to be constructive and pertinent.

Bureaucratic programs, especially Federally funded ones, tend to become "ivory tower," unrealistic programs divorced from reality and from known technology. Since the funds don't belong to a specific individual or Corporation, they seem to belong to no one and are dissipated with little feeling of personal accountability. That's human nature I'm afraid.

Some programs are purposeless or their purpose is vague, obscure or misses the mark. Other extensive and expensive programs simply attempt to redo what has already been accomplished.

Once again Mr. Aidlin, in a letter to Dr. Dixie Lee Ray, Chairman of the U. S. A. E. C., states his thoughts this way;

"Frankly I believe that the program to develop and utilize geothermal energy has been complicated too much. It really is quite simple. What is involved is:

- (1) Exploration and development of geothermal resources. A number of areas have already been explored and discovered. There are adequate fluids in these areas to supply the needs for prototype plants.
- (2) The proof of technology which is immediately available before spending a great deal of money and attempting to develop advanced technology. In this connection there appears to be no technical question as to the viability of the binary cycle. Whether it is as efficient as some other variation can be determined at a later date. If we are to determine the extent of our energy self-sufficiency by the year 1985, it is important to utilize the tools at hand.
- (3) Obtaining a better knowledge of the resource itself. In this connection the drilling of a deep well at the Geysers, another in Imperial Valley, and another in the Gulf Coast area (the first two being proven areas) would certainly give us a tremendous amount of knowledge as to the character of the resource.
- (4) Facilitating the more rapid drilling of various promising areas to get an idea of how much of the resources can be depended upon immediately. This could be accomplished by financial assistance and also by removing the impediments which exist today in connection with the exploration operations. I have always considered it quite illogical to spend a great deal of time, effort and money worrying about environmental effects of the discovery of geothermal resources

in an area before the first well is drilled to determine whether or not the resource actually exists. It would seem to me that a simple program of permitting limited exploration, without the bureaucratic impediments, to determine the presence of the resource and then applying the environmental factors after the character of the resource is known is a much more sensible approach.

I truly believe that if we are to get the best out of the superb research talents of the federal agencies, it is necessary that the projects be scrutinized on a more practical basis before they are undertaken. It is also essential that the private sector be more closely involved and that to accomplish this, the applicable conditions for private involvement be framed so as to meet the legitimate needs and requirements of private industry."

Perhaps our industry's slogan should be: "Our energy needs are great. The hour is late. All sectors should cooperate."

COOPERATIVE EFFORTS BY INDUSTRY AND GOVERNMENT
TO DEVELOP GEOTHERMAL RESOURCES

David R. Butler
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The Federal government's current plans for participation in the geothermal field appear to affect four major areas of interest: (1) resources exploration and assessment, (2) resources utilization projects, (3) advanced research and technology, and (4) environmental, legal, and institutional research. Private industry is also actively involved in these same areas of interest. Because of lack of coordination and communication between the private and public sector, it appears that there will be considerable duplication of effort, and, in some cases, serious conflict. It is also likely that this lack of coordination and communication may result in lack of effort in some key areas. Close coordination and communication between government and industry may resolve some of the major problems that are clearly evident.

The Federal government's current plans for participation in the geothermal field are centered in four major areas of interest:

- (1) Resources exploration and assessment.
- (2) Resource utilization projects.
- (3) Advanced research and technology.
- (4) Environmental, legal, and institutional research.

Private industry is also actively involved in these same areas of interest. Due to lack of coordination and communication between industry and government, it appears that there will be considerable duplication of effort and, in some cases, conflict. Lack of coordination and communication may also result in lack of effort in some areas.

There is cause for concern when the objectives of the Federal program conflict with, and deter, private industry's efforts to find and develop geothermal resources. The "resources exploration and assessment" portion of the Federal program is an example of this conflict. Fiscal year 1975 programs of the United States Geological Survey, the Atomic Energy Commission, and the National Science Foundation all include plans to conduct or sponsor exploration for geothermal resources under the "resources exploration and assessment" effort. Exploration programs are purportedly to develop and improve geothermal exploration techniques or, in the case of the Atomic Energy Commission, to locate test well sites for demonstration plants.

Programs to collect and systematize basic data on a regional basis are projects that could be undertaken by Federal agencies to complement efforts of industry. These programs would include such things as regional geological mapping, systematic compilation of hot spring data, and hydrologic studies. However, Federal programs to develop and evaluate site-oriented exploratory techniques, such as certain geophysical methods, should be limited to those areas where geothermal resources have been proven to exist by previous drilling. It is a waste of tax dollars for the Federal government to gather a mass of exploratory data when these data cannot be related to the actual existence of a geothermal reservoir.

For competitive reasons, industry is forced into this risk-oriented realm. We have to extend geophysical exploration techniques into unproven areas where we may not be certain that our data indicate the presence of a geothermal reservoir. In many instances, the future may well prove that this was also a waste of dollars but these will have been private dollars spent with the full knowledge of the risks involved.

The proof of any exploratory program, be it oil and gas or geothermal, is exploratory drilling which has always been, and will continue to be, a risk venture. The Federal government should not spend tax dollars to participate in high-risk exploratory drilling when there is an industry that will do this job if given the chance.

One example of a government program that is in direct conflict with the exploratory efforts and objectives of private industry is in Nevada, where the Atomic Energy Commission has requested that the Bureau of Land Management withdraw 86,000 acres of Federal land for up to two years while site-oriented geophysical exploration is being conducted in this unproven area. At the end of two years, if geophysical results are favorable, the Atomic Energy Commission will retain a maximum of 5000 acres for up to five years. One or more test wells will be drilled on the retained lands in the hope of discovering a geothermal reservoir of sufficient quality and capacity to furnish the energy necessary for a demonstration power plant.

Any geologist or geophysicist will admit that an exploratory well drilled on the basis of geological and geophysical data and interpretation has some chance, greater or lesser, of failure. In the Nevada example then, what happens if the well or wells drilled on the 5000 acres retained prove to be a failure? Will the Atomic Energy Commission then request that the Bureau of Land Management withdraw another 86,000 acres to do the same thing again? Then, again and again, until statistical success is achieved? It would not take many withdrawals of this size to put Nevada's geothermal prospects out of the reach of private industry on a serial basis. And while the Atomic Energy Commission is trying to find a geothermal reservoir to power a demonstration plant, private industry that wants to get a commercial plant built is forced to stand idly by.

It is significant to note that on the date that the Atomic Energy Commission requested the 86,000 acre withdrawal in Nevada, at least one private company had a geophysical crew at work in the area of requested withdrawal. This company was evaluating whether or not they would file in this area for some of

the 20,480 acres of Federal lands that a private company is allowed to have leased at any one time in Nevada.

In summary of objections to the Atomic Energy Commission's activities in this particular instance, attention is directed to the "Geothermal Energy Research, Development, and Demonstration Act of 1974" just enacted, particularly Conference Report 93-1301 which accompanied the final draft of the bill. Regarding "Resource and Inventory Assessment Program," this report notes that:

"The conference substitute is the same as the House bill, with the following changes: (1) the heading for section 104 of the House bill is changed to reflect the approach taken by the Senate amendments; and (2) the nature of drilling techniques to be used is modified by the conference substitute, to clarify the intent that this research should be to establish the extent and nature of geothermal resources, and should not involve any exploratory drilling which is and should remain the province of private industry."

If the Atomic Energy Commission proceeds with its stated program in this area of withdrawal, there is not only conflict with private industry but with the intent of Congress as well.

Hopefully, this Nevada problem is a symptom of lack of communication between government and industry. Perhaps some in industry were privy to the plans that conflict with industry's aims — others were not. Broader interaction between industry and government in the future will help prevent recurrence of such conflicting situations.

There are ways for industry and government to cooperate in all phases of the proposed Federal program — even in the Resources and Exploration Assessment phase, short of exploratory drilling.

Resources Utilization Projects is an area where Federal programs can aid the efforts of industry. At present, industry intends to explore for, and produce, the natural resource. Public or private utility companies will utilize the resource to produce power. By and large, utility companies are not set up to undertake massive R&D programs to develop new utilization techniques which have some risk of failure. Assistance in this area is vital. However, these efforts to prove utilization concepts should be undertaken in proven reservoir areas. The Federal government should not compete with private industry and hold back industry's efforts by exploring and drilling to find the right area to build demonstration facilities.

Advanced Research and Technology is another area where industry would welcome Federal participation. This is particularly true in the hardware area. Development of hardware in the resources field has traditionally been a service company activity. The service company industry has not been quick to develop geothermal hardware and for good reason. At the present rate of geothermal drilling and development, service companies cannot see that there will be enough demand to justify expenditure of the necessary research funds. The

same principle applies to a great extent in industry research laboratories. Infusion of Federal funds and research at this stage would be most beneficial. As the industry develops and expands, Federal assistance can be phased out as service companies increasingly assume their traditional role.

The Federal government can play an extremely important part in helping industry in the area of environmental, legal, and institutional research. Attempts by private industry to develop geothermal power are encumbered by a bewildering array of environmental, legal, and institutional problems. These problems are not environmental, legal, or institutional per se because there has to be a framework in which we all operate within existing laws and regulations. The problems arise from such things as the lack of pertinent laws and regulations and administrative overlap and duplication. Industry can operate in any fair environmental, legal, and institutional framework as long as we all know the rules. A Federal program of research, education, and aid in implementation could go a long way toward establishing coherent rules.

In summary, industry objects to Federal programs that compete and conflict with their own efforts. On the other hand, industry looks forward to Federal programs which will complement and speed efforts to develop the resource.

A CITY INVESTS IN ITS FUTURE

Joseph N. Baker
City Manager
Burbank, California

Mr. Baker describes events occurring during the past four years which led to the City of Burbank's decision to acquire an energy source adequate for the city's present and future power requirements. The community reaction to this unprecedented move is also covered.

Burbank's long-range plans for the development of geothermal energy are outlined as well as the challenges which confront a public utility in implementing its projected goals. However, Baker cites several advantages accruing to the city which in the opinion of the Burbank City Council and the administration justify this venture. He cites the need for a cooperative climate which will enable all electrical utilities to better meet their obligations to the public, which is their prime responsibility before all other considerations.

This paper, unlike others which have been presented during this conference, is not addressed to the technical aspects of geothermal energy, but deals specifically with "why" the City of Burbank embarked on its own "Project Independence."

I will be the first to acknowledge that this is a most unusual undertaking for a municipality, but we feel that the events which prefaced our entry into the procurement of geothermal leaseholds justify our action. Some data concerning the City and its electrical utility might be of help in understanding this action.

Burbank, California, incorporated in 1911, is located in Los Angeles County. Our community owns and operates an electric power generation transmission and distribution system for the benefit of major industrial and commercial establishments and a resident population in excess of 87,000. Included among the large industries serviced by the Burbank electrical utility are Lockheed Aircraft Corporation, the National Broadcasting Company, Walt Disney Productions, The Burbank Studios (Warner Bros. and Columbia Studios), General Controls, Inc., Zero Manufacturing Company, Menasco, Inc., etc.

The electric power used within the City of Burbank is 788 million kilowatt hours annually. The generating plant has a total capability of 260 megawatts, produced by a combination of gas turbine and steam-electric units ranging in size from 10 to 55 megawatts. These units are designed and

constructed to use natural gas as a primary fuel and to burn residual fuel oil as an emergency or standby source.

The severity of the problem which confronted the City of Burbank during the latter part of 1973 cannot be fully understood without some additional explanation of what occurred in prior years. It is important that events leading to our decision be described.

In the early 1960's, Southern California electric utilities made an attempt to obtain natural gas supplies for the exclusive purpose of electric power generation and to bring those supplies from gas fields located in South Texas through new transmission lines. Opposed to the plan were El Paso Natural Gas Company, Trans-Western Pipeline Company, and Pacific Lighting companies, which include the Southern California Gas Company. These companies intervened before the Federal Power Commission and the California Public Utilities Commission to prevent the construction of the transmission facility. They maintained that there were adequate supplies of gas available through their facilities to supply the needs of the electric utilities through the 1980's and that the building of additional gas transmission facilities would be an unnecessary and costly duplication. In testimony given before the regulatory agencies, statements were made by the gas suppliers that the initial price of 45 cents per million Btu's for delivery of the new gas was excessive and would place an undue burden upon the consumers in the areas to be served. On the basis of these reports, the regulatory agencies denied construction permits to build the required transmission facilities, and the gas supply then available for the new facility was subsequently channeled in other directions.

In 1970, the City of Burbank was advised by its gas supplier that we would no longer be able to receive natural gas in the quantities necessary for our generating purposes. From a natural gas supply of 73% of our required fuel, our gas supply for 1974 is estimated to amount to only 23% of our fuel requirements. This restricted supply of gas has rendered this fuel secondary, or supplemental, and forced the City of Burbank to rely on the oil companies as a primary source, increasing our demand from approximately 285,000 barrels per year to 1,200,000 barrels per year since 1970. As our need for increased supplies of low sulfur fuel oil continued, a small independent refiner kept pace with the needs of the city until November, 1973, at which time we were advised by the company that it could no longer supply us with low sulfur fuel oil and would terminate the contract with the City because its source had withdrawn the supply of crude. Despite continuing efforts on the part of Burbank to obtain a contract we have not, as of this date, been able to obtain any firm commitment for the delivery of low sulfur fuel oil.

We had come to realize prior to the time our contract was canceled that an energy shortage was imminent. However, like all organizations, we, too, find it difficult, if not impossible, to take definitive preventive measures before a crisis exists. Even though the price of low sulfur fuel had increased by almost 300% within a six-month period of time, we were unable to mount an effective campaign for energy conservation on a community-wide basis until we were notified that our contract had been canceled. Concurrently with the cancellation of our contract, Burbank approved a mandatory energy conservation

ordinance which became effective November 26, 1973, and is still in operation today. The Burbank mandatory curtailment program is so effective that we have led the nation in percentage reduction of power usage, and we cannot remove these most stringent restrictions until we have an assured supply of energy for the generation of power.

The City of Burbank also began to search for areas which might give us a reliable source of fuel. We investigated the feasibility of buying into a refinery; we considered entering into an oil exploration venture; and we examined the possibility of contracting directly for oil refined outside the Continental United States. While nothing came of these inquiries, we did lay the groundwork for what was to happen later — our entry into the geothermal energy field.

While we were knowledgeable as to the progress being made in this field, we had not seriously considered geothermal energy as an alternate fuel source until a discussion was held in December of 1973 with Dr. Robert Rex, President of Republic Geothermal, Inc.

These talks progressed rapidly, and the Burbank City Council on January 18, 1974, authorized the submittal of bids for land in three known geothermal areas (KGRA) which were made available on December 18, 1973, by the Secretary of Interior for competitive lease bidding. Quotes were also authorized for other lands categorized as possible geothermal land being offered by the Department of Interior. Our proposals for three KGRA's were accepted, and Burbank found itself plummeted into a new era with geothermal land holdings in the Mono Lake - Long Valley area in Central California and the East Mesa area of Imperial Valley in Imperial County, California.

The City of Burbank has been chastised and lauded for this action. Some have thought the city was courageous, while others were outraged that a municipality would have the audacity to enter into this field.

We moved into this venture with full knowledge of the benefits that could accrue to the city and were also aware of the future that awaits those who invest public monies in any project that fails to materialize — especially a "risk venture." However, the City of Burbank had pioneered before — first, with charter membership in the Southern California Metropolitan Water District; later contracting for electrical power in excess of its needs from the proposed Boulder Dam; and finally, in 1966, investing in the Northwest DC Intertie Line for excess power from the Columbia River Basin. These ventures, too, were considered by some to be courageous and by others foolhardy, especially those projects which were entered into during the 1930's. The end of 1973 found us facing a similar situation.

The City Council action authorizing our entry into the geothermal field was made with many reservations. One unspoken question was, "How will the public accept this decision?" They did not have long to wait for the verdict — the reaction was overwhelming in favor of the decision made by the City Council. Letters from individuals, editorials in the local press, communications from civic clubs, and a resolution adopted unanimously by the Board of Directors of the Burbank Chamber of Commerce endorsed their action, and urged

the City to proceed forthwith. Only a few critics came forward to berate the Council for the initial expenditure of \$1.2 million, or for encumbering the City with a long-term financial obligation for the development of this energy source.

I would advise other governmental agencies to take note of this public reaction, as I believe this illustrates why the "do nothing," or the "let's wait and see" attitudes meet with a great deal of criticism from the electorate at the local level of government.

You might be asking yourself why we, as a city, would make this decision in view of the long-standing precedent that when the situation becomes grave someone will bail us out. Such a question is valid and deserves an answer.

First, our research indicated that we had only encountered the first symptoms of an energy crisis and that this situation would gradually worsen over the long-term future. Second, we knew that we were not considered as a high-priority customer by any supplier of fossil fuel. Third, we realized that due to the age of our equipment a replacement program had to be initiated within the next ten years. Fourth, it was obvious that additional generating capacity would be required to meet the ever-increasing power requirements of the community. Fifth, we realized that storage for fuel was critical. Sixth, we had enough experience with the Air Pollution Control Board and with the various "clean air" groups to realize that the electric industry was not going to be given "carte blanche" permission to operate in a densely populated urban area indefinitely. Seventh, we knew that alternative sources of electrical energy, such as coal fired and nuclear would not be available in the immediate future and, when available, might be prohibitive in cost; and, eighth, it was obvious that the Environmental Protection Agency would require the installation of desulfurization equipment when and if we were allowed to burn high sulfur fuel oil, and that this would be a most expensive undertaking.

A previous recommendation had been made to the City Council advising that if we were to maintain our standards for providing electrical service, it would behoove the City of Burbank to acquire an energy source. This source would provide the assurance that we would have a permanent supply of fuel for generation purposes; that only then would we be in a position to supply electrical power to our customers at the lowest possible cost, and that other problems connected with aging equipment, future environmental control regulations, and the approval needed for the replacement or installation of additional electrical generation capacity within a metropolitan area would be avoided. Therefore, it was decided that the City of Burbank should take advantage of the opportunity to enter into the geothermal field, thereby minimizing our future problems with a planned program of transition, expansion, and independence.

Our third objective, independence, should be welcomed by many industrial representatives attending this conference. Projected requirements indicate that there will be more than enough demand for all available energy even if a large percentage of the public utilities would cease being a customer within the next ten years — however unlikely that might be — and it appears a program similar to the one Burbank has initiated should be encouraged further. However, this has not happened.

The facts indicate that similar action is not being encouraged and, further, the cities are not being consulted. By way of an example, it is interesting to note that the Federal Administration's response to the problem — "Project Independence" — a program whose impact on cities will be quite substantial, excludes the participation of local elected and appointed officials who have an important interest in the shaping of this national strategy. The chief managers of the nation's urban environments, where virtually all of the social, economic, and environmental consequences of the expanded energy source development will become manifest, have been effectively eliminated from meaningful participation in the development of this plan.¹

The very fact that municipalities have been excluded from the establishment of national policy makes it more imperative that Burbank proceed with the development of geothermal as our prime source of energy for power generation. We have taken, and we will continue to take an active role in attempting to influence the legislation relating to geothermal energy being considered by the Congress. We have been interested specifically in assuring that equal consideration is given to municipalities and public utilities in all public laws which relate to the exploration or development of geothermal energy. We propose to maintain our interest in future legislation of this type.

Further, while the City of Burbank entered into the geothermal field in an attempt to solve a very perplexing problem facing one community, we are also interested in cooperating with other participants, public or private.

Burbank's situation is insignificant in comparison to energy shortages facing other municipalities located in Southern California, and the energy problems facing municipalities in Southern California are overshadowed by those facing this nation. I would hope that the practices of the past could be set aside; that the long-term disputes between public and investor-owned utilities could be ended; and that past priorities could be reevaluated in order that we can maximize all of our energy resources for the benefit of the public. This is our first obligation, and also our joint responsibility.

¹"Doubts Surfacing About Administration's Energy Program", City Perspective, National League of Cities and U. S. Conference of Mayors, August 1974.

GEOHERMAL STEAM CONDENSATE REINJECTION

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Geothermal electric generating plants which use condensing turbines generate an excess of condensed steam which must be disposed of. At the Geysers, California, the largest geothermal development in the world, this steam condensate has been reinjected into the steam reservoir since 1968. A total of 3,150,000,000 gallons of steam condensate has been reinjected since that time with no noticeable effect on the adjacent producing wells. Currently, 3,700,000 gallons/day from 412 MW of installed capacity are being injected into 5 wells. Reinjection has also proven to be a satisfactory method of disposing of geothermal condensate at Imperial Valley, California, and at the Valles Caldera, New Mexico.

The Geysers is a vapor-dominated reservoir with a reservoir pressure not exceeding 500 psig. Since the average depth of the injection wells is 5380 feet, no pumping of the injected water is required. The surface facilities consist of a settling basin to remove solids, transfer pumps, deaerating vessels, and fiberglass or plastic-coated steel pipelines.

I. INTRODUCTION

The native fluids produced from most geothermal systems recover only a fraction of the total energy within the system. The most apparent method of recovering additional heat from the system is to inject cold water back into the reservoir to extract heat from the reservoir rock. Also, geothermal electric generating plants which use condensing turbines generate an excess of condensed steam which must be disposed of. So even vapor-dominated or dry steam fields will have large volumes of excess steam condensate and liquid-dominated or hot water fields will have even larger volumes to dispose of.

The simplest and most economical method of disposing of this water and condensed steam is to reinject it into the geothermal reservoir. The alternatives to this course of action are either surface disposal or underground disposal in zones other than the geothermal reservoir. To purify the water adequately for surface disposal is often very expensive and disposal zones other than a geothermal reservoir are often not available in many areas of the country. The Union Oil Company has operated geothermal condensate

reinjection projects at the Geysers and Imperial Valley, California, and at the Valles Caldera, New Mexico. The purpose of this paper is to provide a case history for each of these projects.

II. THE GEYSERS

At the Geysers, a vapor-dominated reservoir, steam condensate reinjection back into the reservoir began in 1969, and 3,150,000,000 gallons of condensate have been reinjected since that time. Currently, 3,700,000 gallons per day from 412 MW of installed capacity are being injected into 5 wells.

The condensed steam is essentially fresh water, although there is a small volume (about 1%) of other gases in the steam, some of which is soluble in the steam condensate. These contaminants, principally ammonia and boron, are present in concentrations in excess of the limits set by the Regional Water Quality Control Board for discharge directly to the watershed.

The condensed steam is received from the cooling tower basins of the electric generating plants and piped to settling basins. These settling basins are approximately 50 X 50 ft and 8 ft deep, constructed of concrete with wooden baffles, and are designed to remove any settleable solids from the effluent. Level control valves are installed on the outlet of these basins to insure that no air is allowed to enter the discharge pipe that leads to the injection wells. From the settling basin, the water either flows by gravity or is pumped through plastic-coated welded steel pipelines to the injection wells. Deaerating vessels are installed on the lines as an additional precaution against air being injected into the wells and causing corrosion problems. A continuously recording orifice meter is also installed in the pipeline to record the volume of water injected into each well.

All of the five injection wells were originally drilled as steam production wells and then converted to injection service. The wells are drilled with water-based drilling fluid down to the top of the steam reservoir where a string of 9-5/8-in. casing is set. The producing interval is drilled using air as the circulating medium to the total depth of the well. Producing wells are left in this condition, but conversion to injection requires that a slotted liner be placed through the injection interval to prevent the formation from sloughing into the wellbore on contact with water (Fig. 1).

The Geysers steam reservoir is a fractured Graywacke with steam production occurring from a few hundred feet to over 9000 ft in depth. The initial reservoir pressure is about 500 psi. Since the injection wells have depths ranging from 2364 to 8045 ft, this low reservoir pressure causes a large pressure differential towards the formation, and the wells will inject large volumes of water without requiring pumping. The high permeability-thickness products (from 20,000 to 150,000 millidarcy feet) encountered in the wells are also a factor in the high injection rates (1200 gallons/minute) with no backpressure at the wellhead.

The locations of the injection wells are chosen such that they are as far as possible from existing producing wells and the injection interval is deeper than the producing interval in the adjacent producing wells. This precaution has so far been sufficient to prevent communication of the injection water to the producing wells. The importance of injection depth was illustrated early in the life of the injection project when communication from the first injection well to a nearby producing well was established. A spinner survey run in the injection well showed that due to a bridge in the wellbore, the water was being injected at a shallower depth than anticipated. The injection well was then cleaned out to total depth and a slotted liner run. The well was returned to injection and has been on injection for five years with no further evidence of communication.

There have been some problems with the injectivity of individual wells declining with time. The cause of this has been attributed to plugging of the fracture system with elemental sulphur in the steam condensate. This problem is easily overcome by shutting the well in and letting it heat up. Since the melting point of sulphur is 238°F and the reservoir temperature is 475°F, the sulphur is easily melted and can be pushed away from the wellbore and back into the formation.

The Division of Oil and Gas is the state agency responsible for regulation of geothermal reinjection projects. Before approving the project, they examine the geologic and engineering data, including reservoir conditions, injection fluid volumes and analyses, geologic maps, and cross-sections. They also must approve the drilling or conversion of each individual injection well. A report on the injection volumes is sent to the Division of Oil and Gas on a monthly basis. The water quality of the adjacent watershed is also monitored monthly.

The USGS is monitoring both seismically and by methods of triangulation any land movements that might occur as a result of our injection program. The data indicate that there is no noticeable change in the seismic activity within the area.

III. VALLES CALDERA, NEW MEXICO

Union Oil's reinjection experience at the Valles Caldera is a result of production testing two geothermal wells in that area during 1973 and 1974. The reservoir is a liquid-dominated reservoir, and the fluid flashes to a mixture of steam and water when the wells are produced. The wells were flowed through a steam-water separator and the water was flowed into holding ponds and then pumped to the injection well. The test has been underway for a little over a year, and during this time almost 100,000,000 gallons of water were reinjected. There have been no evidences of injectivity impairment during that time.

IV. IMPERIAL VALLEY

Union Oil's reinjection experience in the Niland area of the Imperial Valley is again the byproduct of a production test. This test was of one year's duration during 1964 and 1965. The reservoir is liquid-dominated and static wells have a wellhead pressure of 200 psig. After initially overcoming this pressure, the heavier column weight of the cold injection water allowed the injection well to take water at a vacuum. During the one-year test, approximately 126,000,000 gallons of water were reinjected. The injection rate into the well was approximately 600 gallons per minute. Again, there was no loss of injectivity during the test and there was no reservoir response.

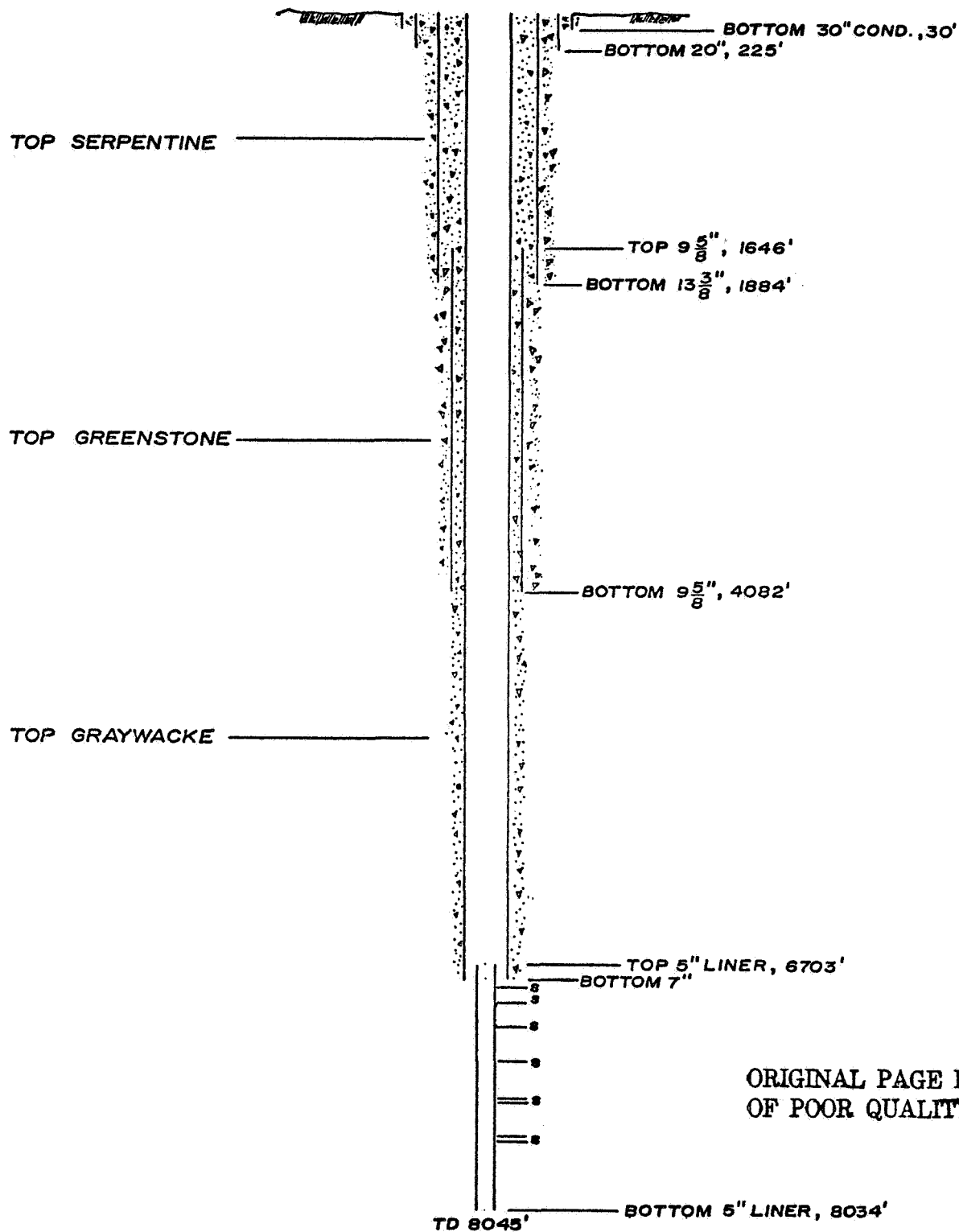


Fig. 1. Typical Injection Well

UTILITY COMPANY VIEWS OF GEOTHERMAL DEVELOPMENT

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San Diego Gas & Electric Company
San Diego, California

The statement will emphasize views of geothermal development from a utility company standpoint. The impediments associated with such developments as required reliability and identification of risks will be discussed. The utility industry historically is not a risk-taking industry. Support of rapid geothermal development by the utility industry requires identification and elimination of risks or absorption of the risks by other agencies. Suggestions as to the identification and minimization of risks will be made.

I. INTRODUCTION

In most geothermal development projects, electric power generation utilizing the geothermal resource is considered an electric utility; this utility will be involved in the project as the ultimate purchaser of electrical energy or, more likely, the purchaser of the geothermal fluids which will be utilized in the utility owned and operated generating plant.

A utility may choose to participate in a project in the early exploration stages or wait until this phase is done by others and join a project at the time the reservoir capacity has been established. In both cases the utility will need certain criteria established prior to committing to the purchase of electrical energy from a generating plant or the construction of a generating plant utilizing a given resource. There are four major areas of concern on which a utility must have facts to actively develop a geothermal resource. These four areas are :

- (1) The need to have established reliability.
- (2) The need to have assurance of reservoir capacity.
- (3) The need to have assurance that the economics of a geothermal development are comparable to the utility's other alternatives.
- (4) The need to integrate a geothermal development program into existing power generation expansion plans.

Each of these areas will be discussed separately in the following.

II. RELIABILITY

The prime goal of an electrical utility is to provide reliable service to its customers. This goal is reflected throughout all of the equipment in the

utility's system. The power production facilities must have an established reliability record to fit into the overall goal of the utility.

In considering a geothermal development the reliability of the equipment will be of utmost concern to the utility participant in the development. Reliability concepts will not be accepted by the utility industry solely from engineering feasibility studies. Operational field testing on all hardware associated with the process will be desired prior to commitment by the utility to a process to be incorporated into its overall electric generating plans.

In the case of dry steam, operation at The Geysers has demonstrated reliability and should additional dry steam fields be found demonstration would not be necessary. The reliability of equipment associated with the utilization of a pressurized hot water reservoir does need field demonstration for the utilities to seriously consider it in their overall generation plans.

III. RESERVOIR CAPACITY

A utility will have to rely completely on the supplying reservoir for the "fuel supply" for a geothermal generating plant. Therefore, prior to expending any significant amount of funds on a geothermal project a utility will desire to have the risk associated with reservoir capacity defined and, if possible, eliminated.

In locations remote from the utility's area of service reservoir capacity will have a significant effect on the economics of a project. The greater the distance that a reservoir is from the point of usage of the electric power the larger the assured capacity will have to be to support the electrical transmission system. A general rule of thumb is that for every mile of transmission line required, two megawatts of reservoir capacity (for a 20 - 30 year period) will be necessary to support the construction of the transmission line.

Data developed in demonstrating reservoir capacity must withstand the independent review of competent firms in the reservoir assessment field.

IV. ECONOMICS

For a utility to participate in a geothermal development project the overall cost of electrical energy from that project to the point of the utility's utilization of that energy must be competitive with the utility's other alternatives. In the long term geothermal energy must be competitive with coal and nuclear generation facilities. In the short term there may be the opportunity for geothermal power generation to displace fuel oil in existing fossil fuel burning plants. In this case the overall cost of the geothermal power need only be less than the cost of the fuel oil being used in a fossil fuel plant. It must be kept in mind that in order for a utility to take advantage of this type of displacement of fuel oil a sizeable financial investment will be required to install the generating facility if the utility itself is the owner of the power plant. With utility's vast requirement for capital this may require the developer to participate in the funding required for a geothermal plant to displace fuel oil in existing generating facilities.

V. EXISTING EXPANSION PLANS

Most utilities have generation expansion plans that have facility commitments for various types of generation for the next ten years. Nuclear powered and coal-fired generating plants are the baseload type of energy that utility companies are planning for the future. Because of the long lead time requirements associated with these types of facilities significant financial commitments are being made today for generation facilities that will be on the line in the 80's. The lead time required to have a coal-fired plant on the line is approximately 7 to 8 years and a nuclear plant 9 to 10 years. Because of this the utilities do not have a great deal of flexibility to integrate into their expansion plans for the next 8 to 10 years any major emerging geothermal resource. This is the case if a geothermal project is looked at as one of supplying the capacity requirements for the expansion of the utility system. If the geothermal project can be considered as one that displaces existing fuel oil in plants presently on line the problem associated with integration into an expansion plan is not critical.

VI. SUGGESTIONS ON GOVERNMENT PROGRAMS

It has been stated that the goal of the government programs is to accelerate the development of geothermal energy. Therefore, the areas that should be concentrated on are establishing reliability, reservoir capacity assurance, and economic feasibility. It has also been stated that the government desires not to operate within a vacuum but to participate in the acceleration of the geothermal program with industry.

The binary system of power generation appears to be a good selection for the utilization of the pressurized hot water reservoirs. A great deal of engineering has been done on this process and it appears that it will be economically feasible. What needs to be done now is to develop a field operating facility to establish the necessary reliability of the process to enable its use to be considered for various pressurized hot water reservoirs. Government should assist industry in bringing this to fruition as quickly as possible. The technical areas where research concentration is needed on the binary process is the pumping of the wells and the mitigation of the scaling and corrosion phenomena associated with the geothermal fluids.

For rapid development to occur on geothermal projects a high level of confidence in the reservoir capacity must be reached as quickly as possible. Present reservoir engineering techniques rely heavily on production of the field to establish trends which will enable projections to be made of reservoir capacity. Efforts should be concentrated on developing reservoir modeling techniques so that years of operation are not required to establish high levels of confidence in the reservoir capacity. This is an area that merits government participation with industry to aid in the acceleration of the geothermal program.

Many new concepts for power generation utilizing geothermal fluids have been proposed. These may improve the efficiency and economics of utilizing the geothermal resource, but are still in the high risk category. This should

be supported by government activity to assist in the long range program of improving the overall economics of geothermal energy.

As a general philosophy on the acceleration of commercial geothermal development, government participation can best aid acceleration by providing the preliminary funding of a commercial project while the activities associated with demonstrating reliability and reservoir capacity are proceeding. Normally a utility will not commit to a major development project until reliability and reservoir capacity have been demonstrated. This could take up to two years of operating time of a small scale test facility. If it is assumed that the reliability and reservoir capacity will be demonstrated, the initiation of environmental assessment work and engineering on the major development can be carried out in parallel with the small scale testing. With government assuming this risk in the early portion of the major project, the utility can take over the funding at the instant that the risks have been eliminated. As much as two years can be cut in the schedule for the major facility by this type of government participation.

A NEED FOR FOCUSING GEOTHERMAL RESEARCH AND DEVELOPMENT EFFORTS

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This presentation discusses the importance of focusing the National Geothermal research and development program on a few key geothermal types which show the most promise for early development. Specifically, the discussion focuses on the need for a concerted effort to develop medium-temperature hydrothermal sources.

The Federal Government program has projected a total generating capacity of some 20,000 MWe by 1985 from geothermal energy. This program objective was formulated with very limited input from the electric utility industry and has not considered the management risks, financing or long-term planning required by the electric utility industry in introducing new generation systems. Further, the federal program does not discuss the specific need for demonstration projects which will provide the concrete basis for electric utility management to define risks associated with geothermal resources of various types. A close working relationship between the electric utility industry, EPRI, and the federal program is necessary to define program requirements from the user standpoint.

Our assessment at EPRI indicates that the next potential source for major development is medium-temperature, low-salinity hydrothermal sources. To date, only two major reservoir programs to define the capacity of such reservoirs have been performed. These are the combined efforts of San Diego Gas & Electric Company, Magma Power and Chevron at the Heber Site in the Imperial Valley, and Union Oil in the Valles Caldera of New Mexico. All other geothermal capacity projections have been made with little, if any, well data to substantiate either resource characteristics or reservoir capacity. It is imperative that a more quantitative evaluation of alternative sites be performed, including a major drilling program, if we are to achieve significant electric generation potential from geothermal sources in the 1985 to 1990 time period. A specific federal research effort to define the effects and importance of site-to-site variability of hydrothermal resources on the kinetics of deposition in heat exchanger tubes, effects on downhole pumps, reinjection problems, etc., is necessary to minimize risks associated with hydrothermal resource development.